Bioventing

Battelle Memorial Institute

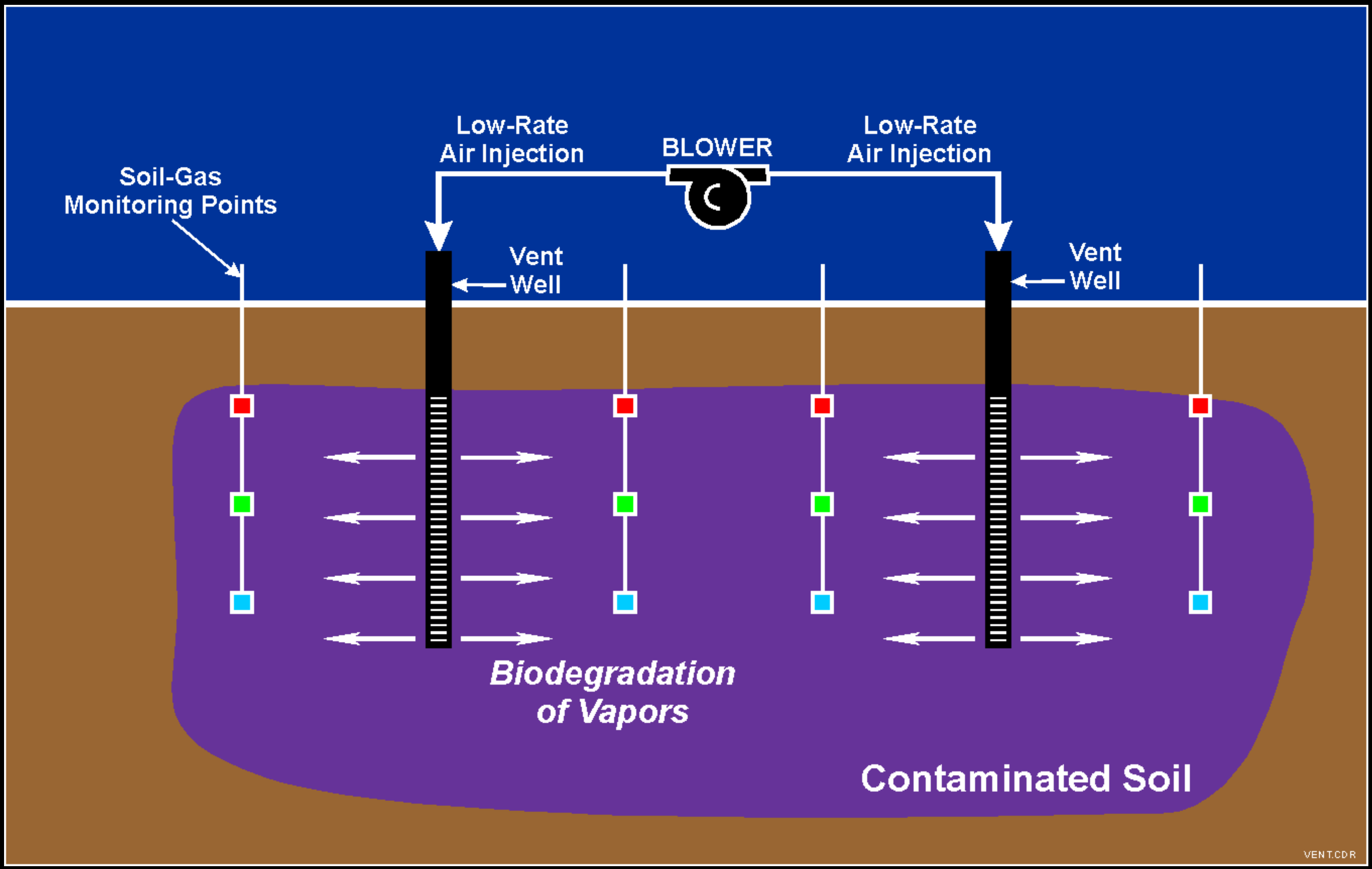
Topics Covered

- Principles of bioventing
- Practical information for implementation of bioventing
  - Site characterization
  - Field design
  - Process monitoring
  - Site closure
- Cleanup times and costs
- Questions and answers

Bioventing

- Subsurface injection or withdrawal of air to stimulate biodegradation
- Similar to SVE, but with significantly different objectives
  - maximize biodegradation
  - minimize volatilization
- Applicable to any aerobically biodegradable compound

Schematic Diagram of a Typical Bioventing System



Significant Features of Bioventing

- Optimize flowrates to minimize volatilization, while maximizing biodegradation
- Monitor local soil-gas concentrations, not just off-gas, to ensure adequate aeration
- Conduct tests to measure biodegradation in field

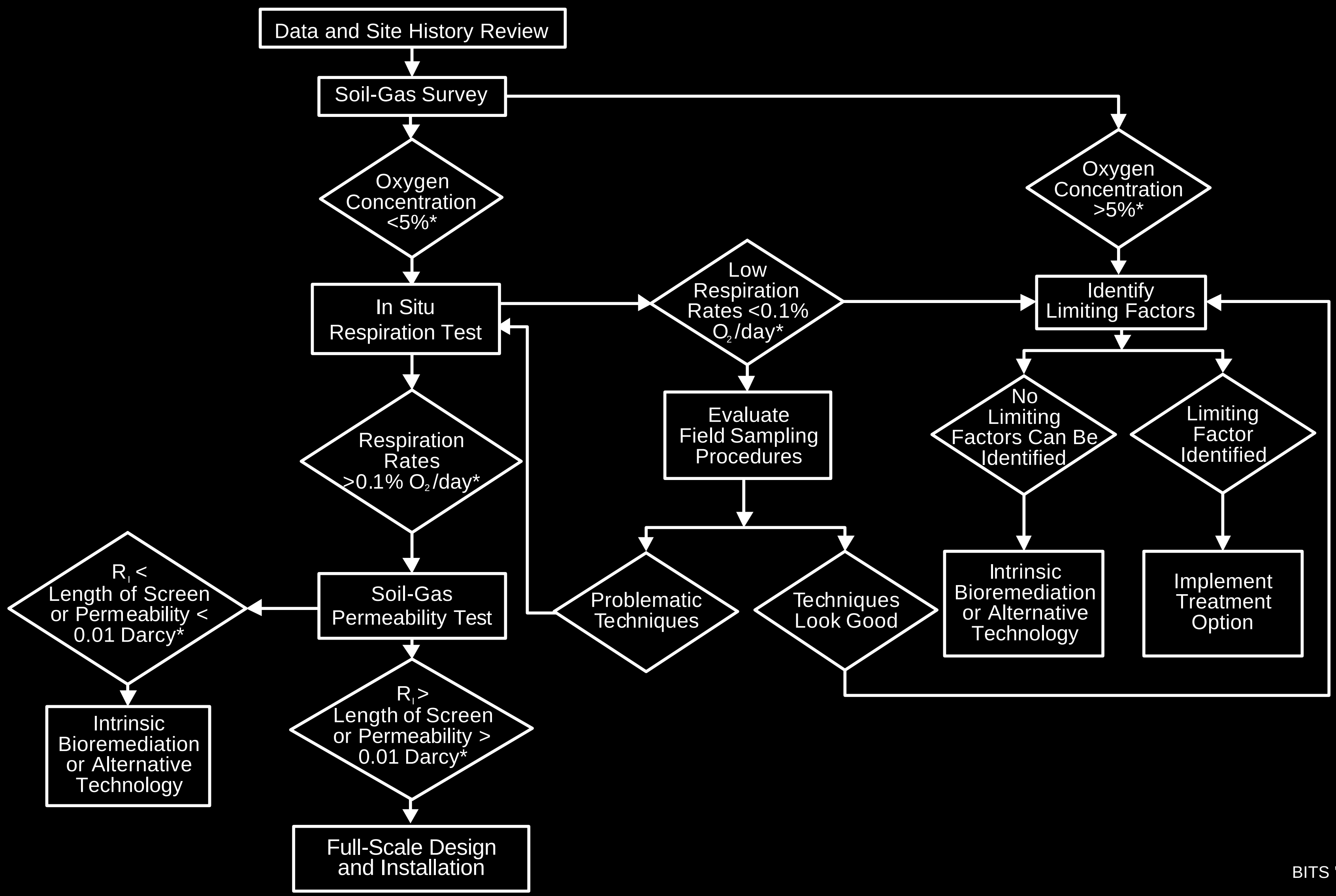
Factors Limiting Bioventing of Contaminants

- Most Important Factor
  - ***Oxygen*** (petroleum hydrocarbons and other aerobically degraded compounds)
- Other Factors
  - Carbon source (chlorinated compounds)
  - Temperature
  - Moisture
  - Nutrients
  - Bioavailability

Bioventing Design

- Site characterization activities
- System design
- Performance monitoring
- Process evaluation/site closure

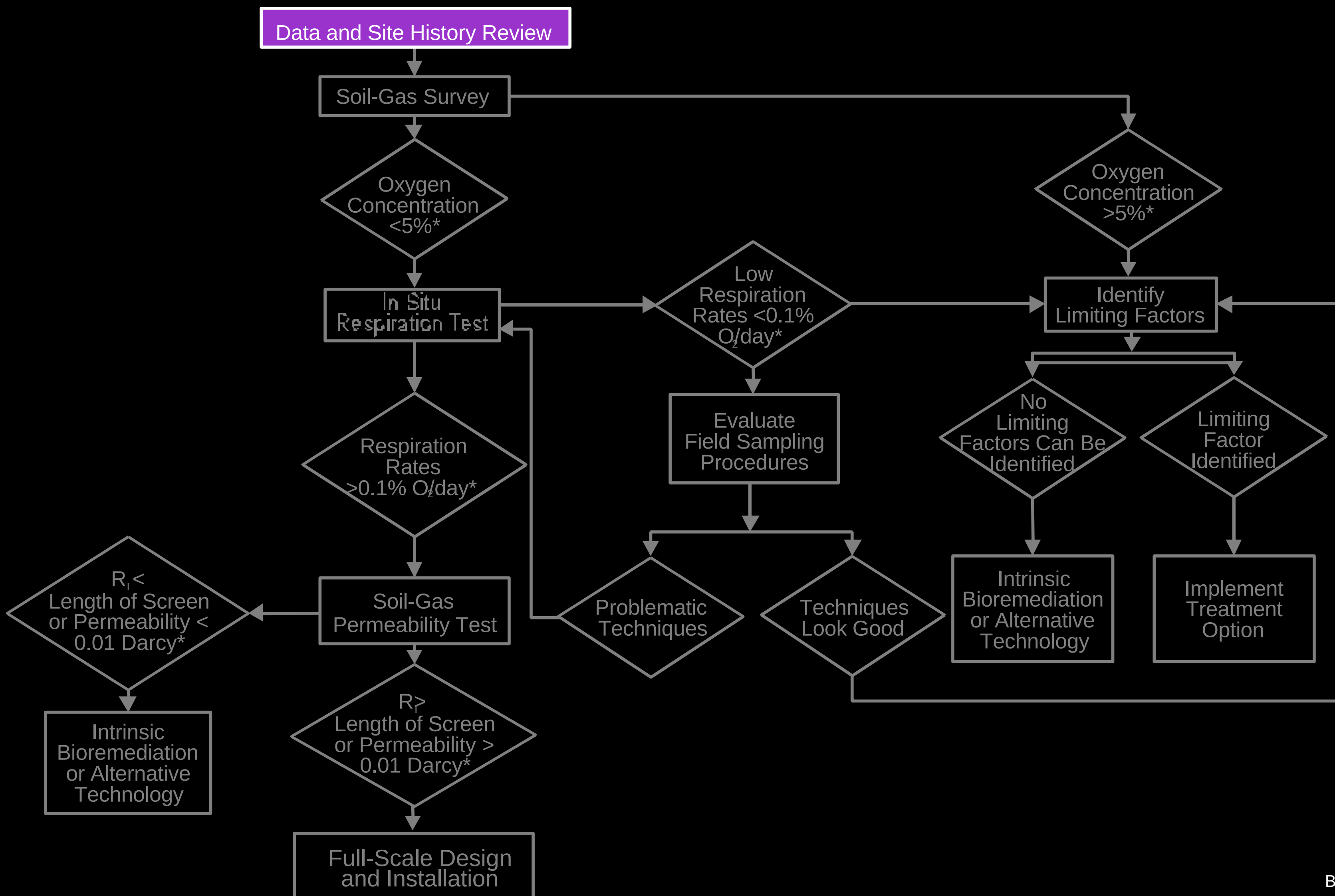
Flow Chart for Determining the Potential Applicability of Bioventing at a Contaminated Site



Site Characterization Activities

- Review existing site data and history
- Soil-gas survey
- In situ respiration test
- Soil-gas permeability test
- Soil characteristics

Flow Chart for Determining the Potential Applicability of Bioventing at a Contaminated Site: Data and Site History Review



Review of Existing Data and Site History

- Type of contaminant
  - Petroleum hydrocarbons very well suited to bioventing
  - Any other aerobically degradable compound
  - Chlorinated solvents (modification to traditional bioventing system required)
- Amount and distribution of free product
  - Free-product removal may be necessary

    ↪ consider bioslurping

Review of Existing Data and Site History (cont.)

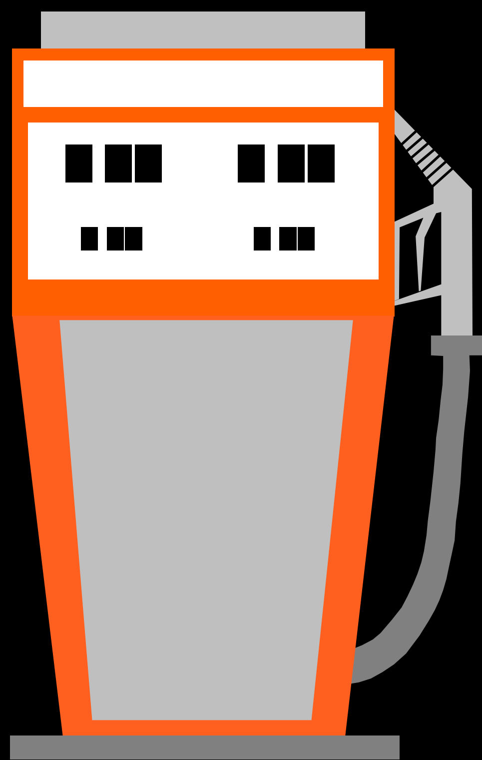
- Historic water table levels
  - Water table fluctuations may have smeared contamination below current water table depth
- Permeability
  - Soil must be permeable enough to allow air movement
  - Sandy soils are ideal; clayey soils possible

Review of Existing Data and Site History (cont.)

- 3-D distribution of contaminant
- Source location - continuing contamination?
- Surface features such as concrete or asphalt
  - May result in higher costs if subsurface installations are required
  - May increase radius of influence

lower installation costs

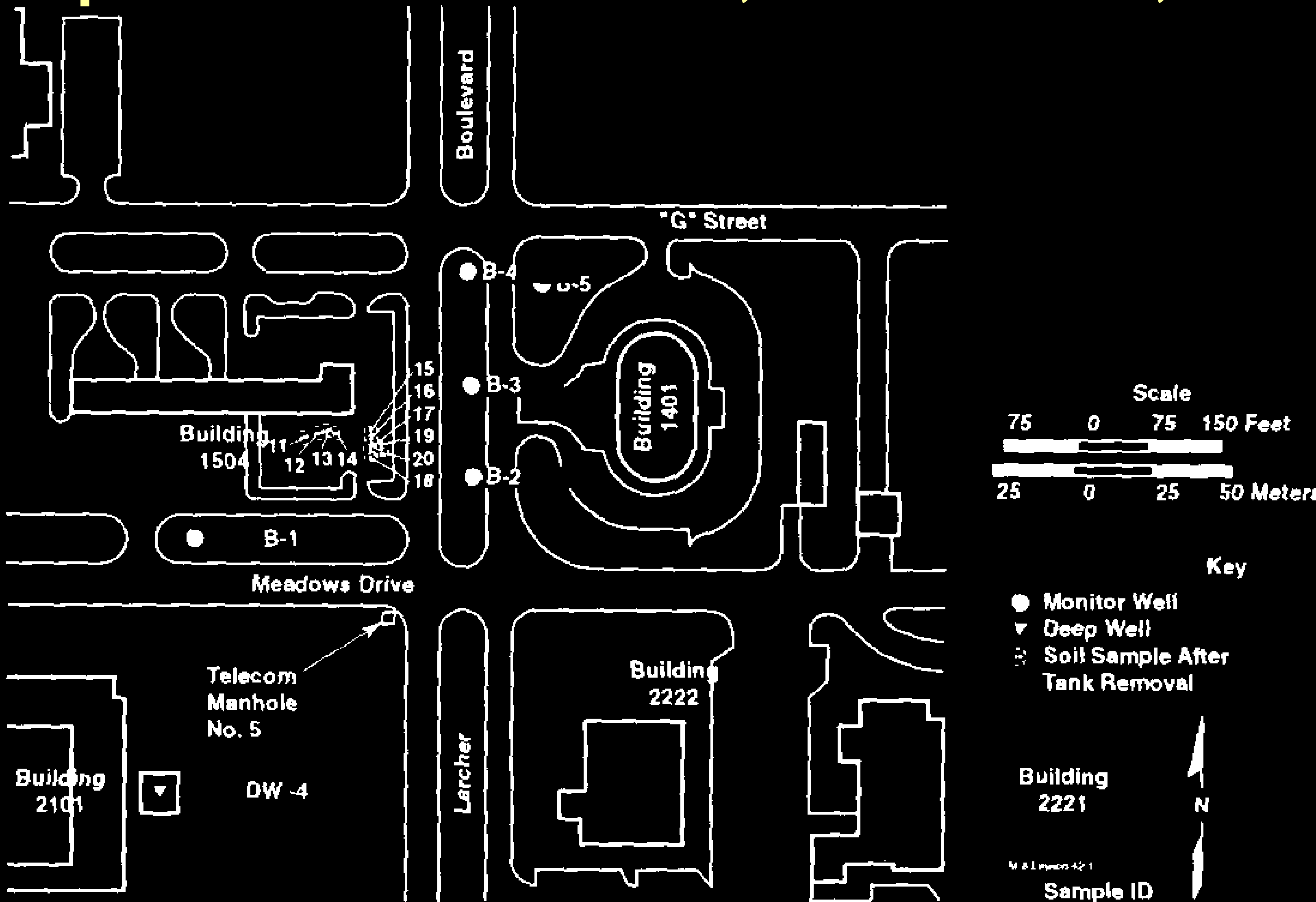
Review of Existing Data and Site History for a Gasoline Station



Base Gas Station, Keesler AFB

- Base service station
- Leaking underground gasoline storage tanks
- Tanks removed in 1991
- Soils are very sandy
- Provided with site map

Site Map of Base Gas Station, Keesler AFB, MS



	11	12	13	14	15	16	17	18	19	20	West	North	East	South
TPH (mg/kg)	–	85.6	77.6	–	1030	1010	540	–	741	814	–	1850	1640	756

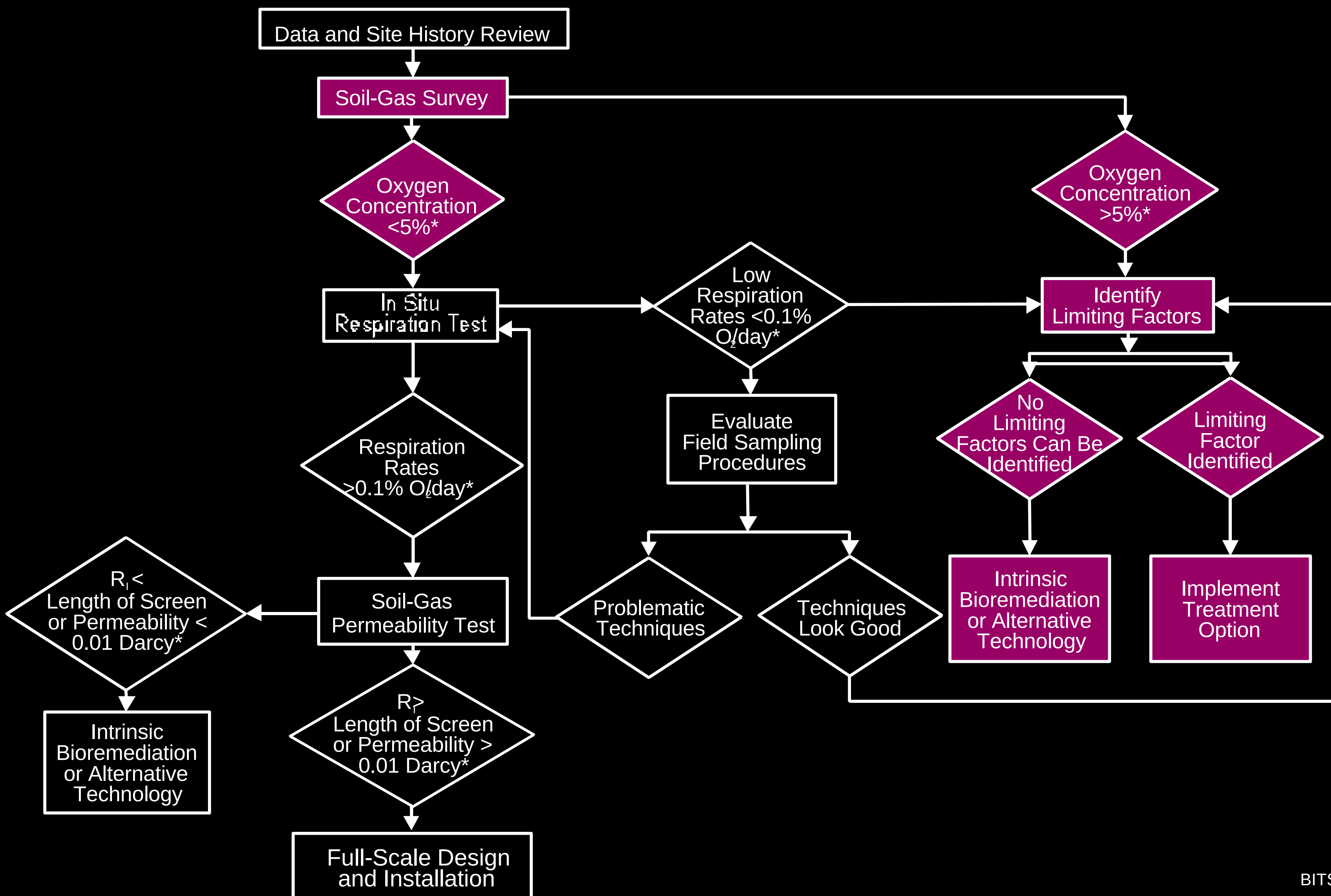
Data Evaluation

- What data is missing?
- Can we proceed with site characterization based on available data?

Data Evaluation

- What data is missing?
  - ☑ Type of contaminant
  - ☐ Missing: Free-product information
  - ☐ Missing: Historic water table levels
  - ☑ Permeability
  - ☐ Missing: 3-D distribution of contaminant
  - ☑ Source location
  - ☑ Surface Features
- Can we proceed with site characterization based on available data? *Yes!*

Flow Chart for Determining the Potential Applicability of Bioventing at a Contaminated Site: Soil-Gas Survey



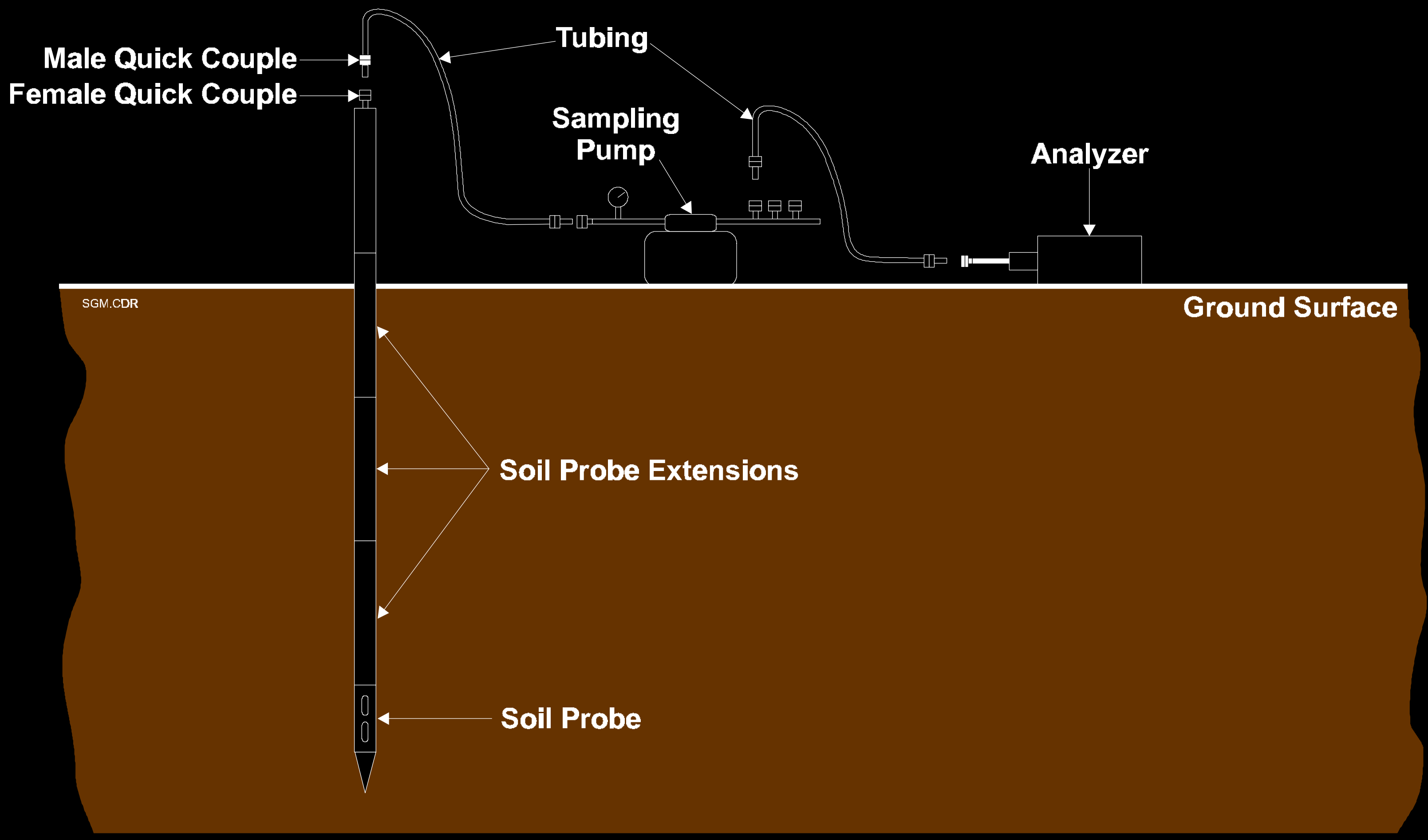
Soil-Gas Survey

- Applicable to shallow soils, only useful if probes penetrate to treatment depth
- Confirm oxygen limitation
- Assist in delineation of contamination
- Assist in locating monitoring points and vent wells

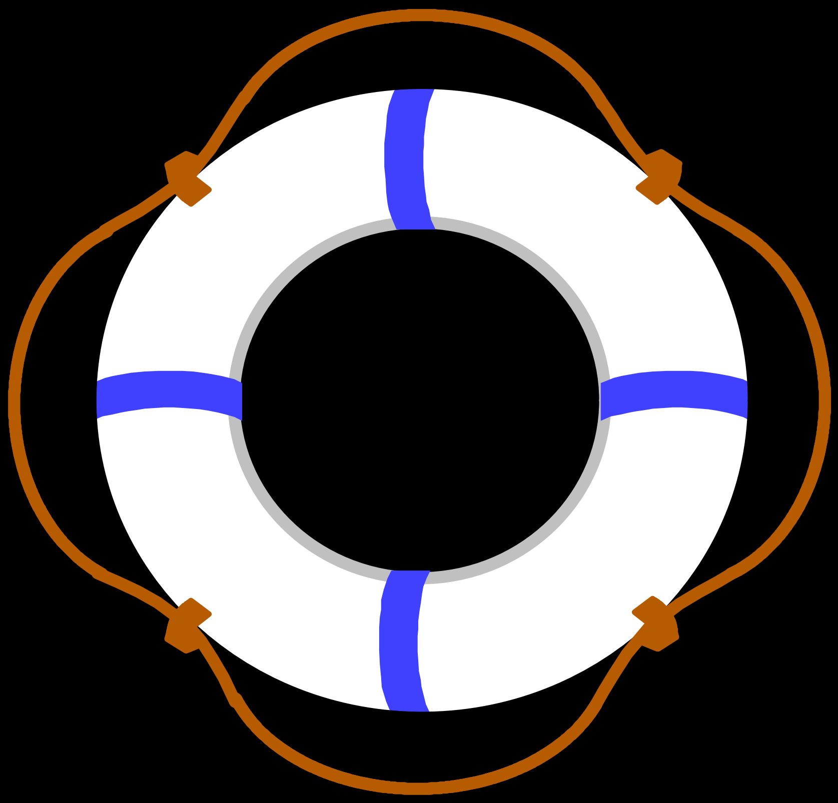
Soil-Gas Characteristics

- Low oxygen (<5%)
- High carbon dioxide (10%)
  - Depends on soil chemistry Could be low but site is still favorable
- High TPH (>10,000 ppm)

Soil-Gas Sampling System Using the Stainless Steel Soil-Gas Probe



Soil-Gas Survey Results at the Aquasystem Site, Westover AFB



Soil-Gas Survey Results: Aquasystem Site

SGS Point	Depth (ft)	O_2 (%)	CO_2 (%)	TPH (ppm)
PT1	3.0	16	3.2	60
	6.0	12.5	5.0	60
PT2	3.0	15.5	4.3	72
	6.0	13	6.0	74
PT3	3.0	18	2.6	74
	6.0	12	6.2	84
PT4	3.0	16	4.0	86
	6.0	11.5	5.0	80

Analysis of SGS at Westover AFB

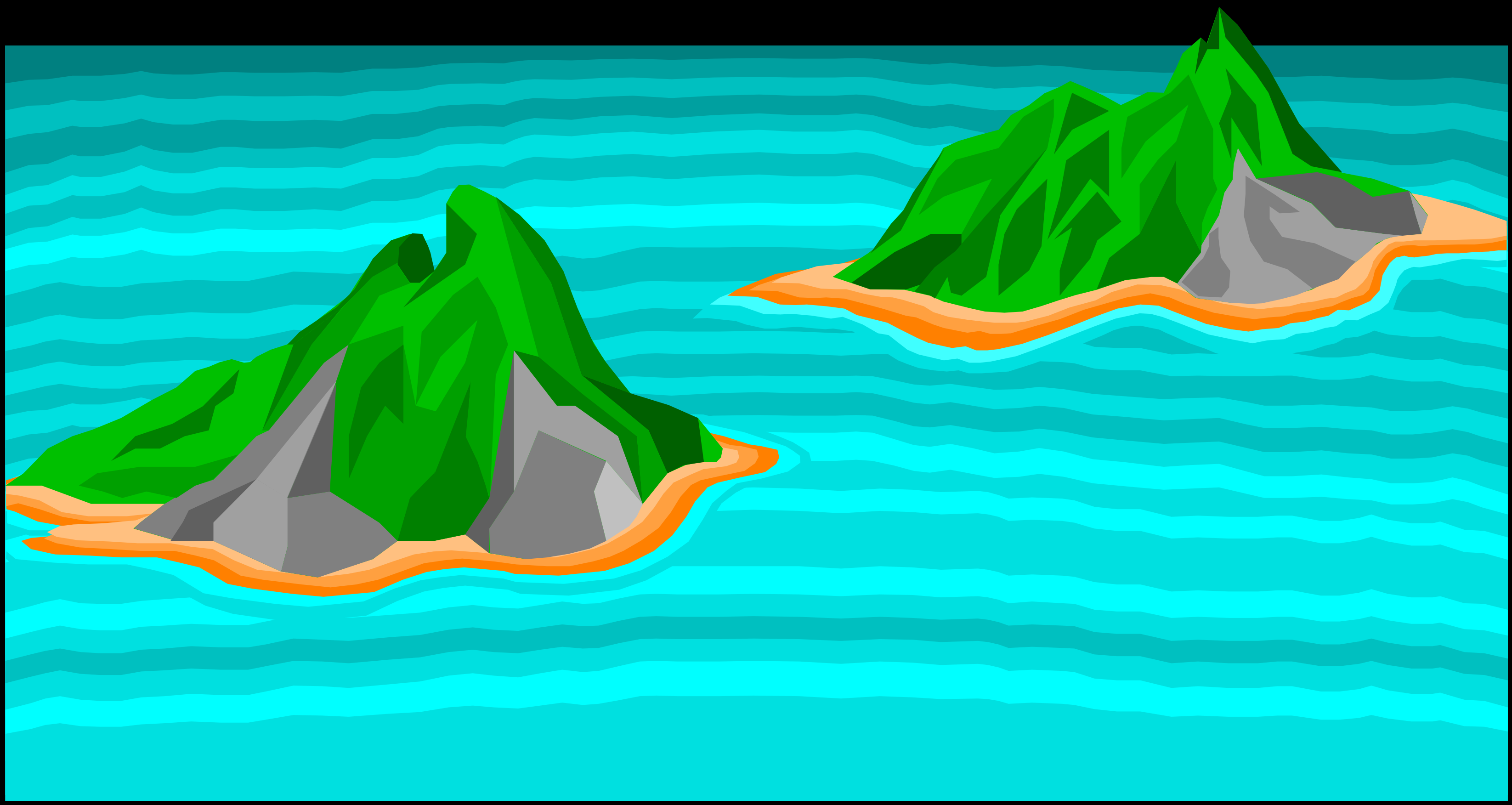
- Is this site a potential candidate for bioventing?

Analysis of SGS at Westover AFB

- Is this site a potential candidate for bioventing?
  - In general, oxygen is not depleted below 5%
  - Carbon dioxide is only slightly elevated
  - TPH concentrations are relatively low

☑ Site is probably naturally attenuating
☑ Bioventing would probably not stimulate faster remediation

Soil-Gas Survey Results at the Old Fire Training Area, Johnston Atoll



Soil-Gas Survey Results: Johnston Atoll

SGS Point	Depth (ft)	O_2 (%)	CO_2 (%)	TPH (ppm)
SGS1	2.5	3.1	14.0	1,420
SGS2	2.5	5.6	14.9	220
SGS3	2.5	12.6	7.9	116
SGS4	2.5	2.5	14.2	920
SGS5	2.5	3.3	12.0	146

Analysis of SGS at Johnston Atoll

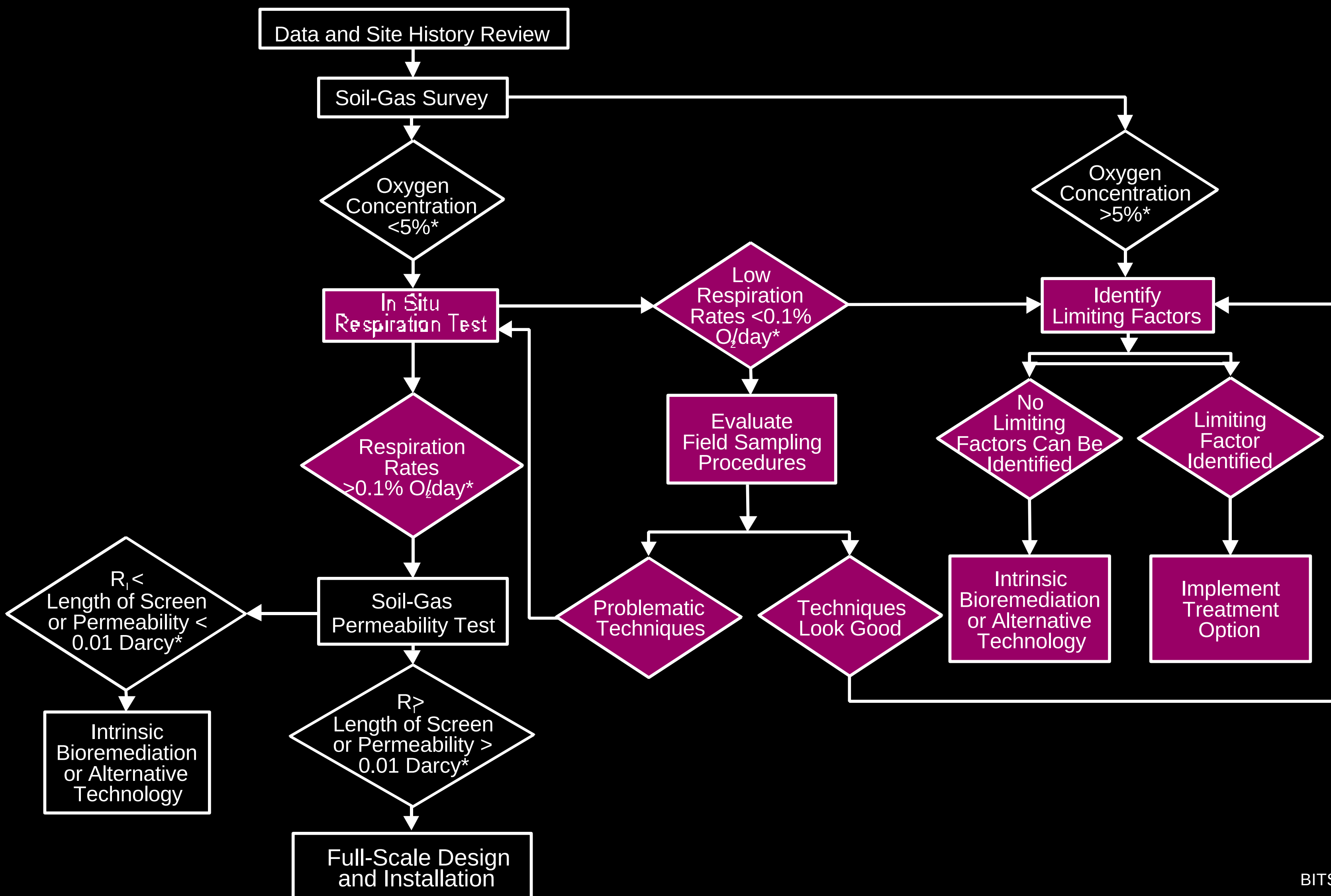
- Is this site a potential candidate for bioventing?

Analysis of SGS at Johnston Atoll

- Is this site a potential candidate for bioventing?
  - In general, oxygen is depleted below 5%
  - Carbon dioxide is elevated
  - TPH concentrations are relatively high

☑ Bioventing appears to be a feasible option for this site. Proceed with site characterization.

Flow Chart for Determining the Potential Applicability of Bioventing at a Contaminated Site: In Situ Respiration Test



In Situ Respiration Test

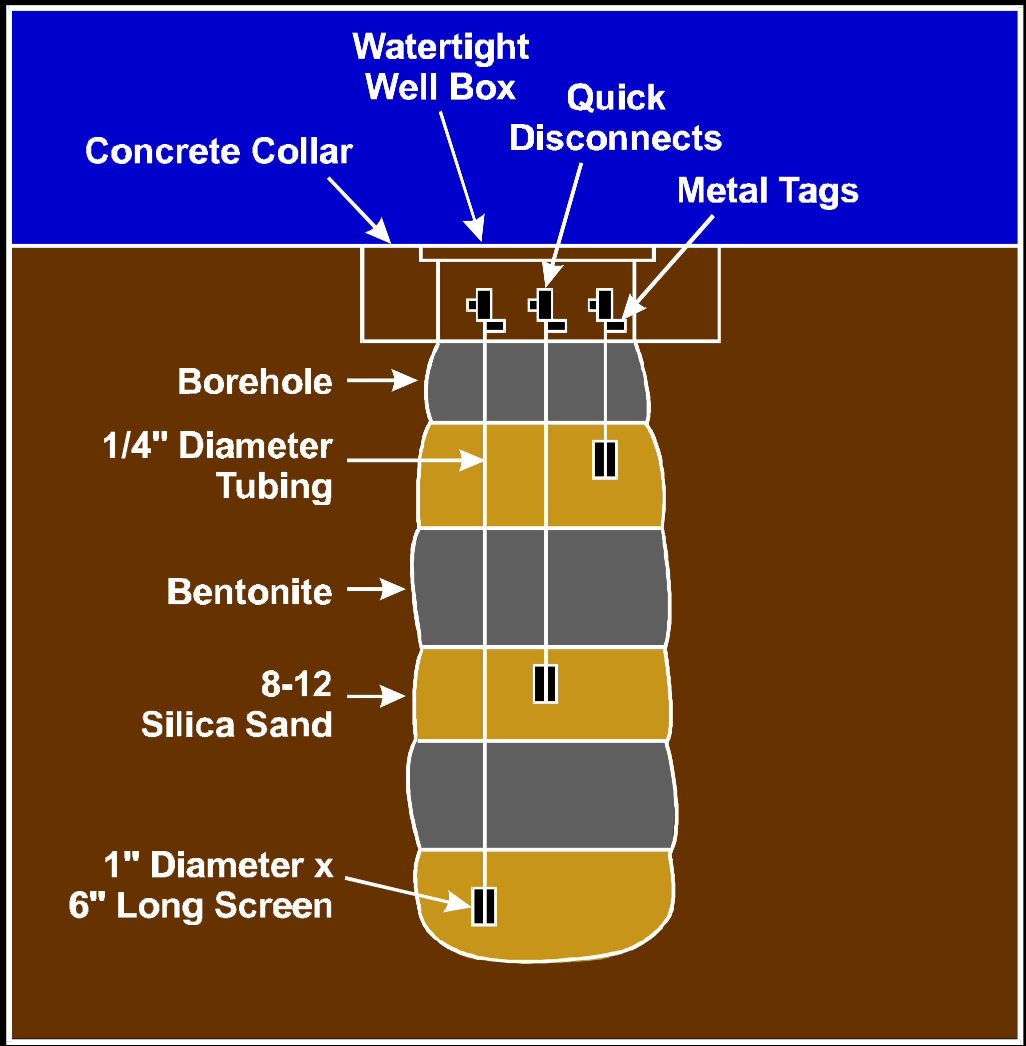
- Measure of activity of microorganisms
  - Calculate a rate of oxygen utilization
- Relate to degradation of contaminants
  - Estimate degradation in terms of mg contaminant per kg soil per day
- Field measurement

➥ more accurate than laboratory measurements

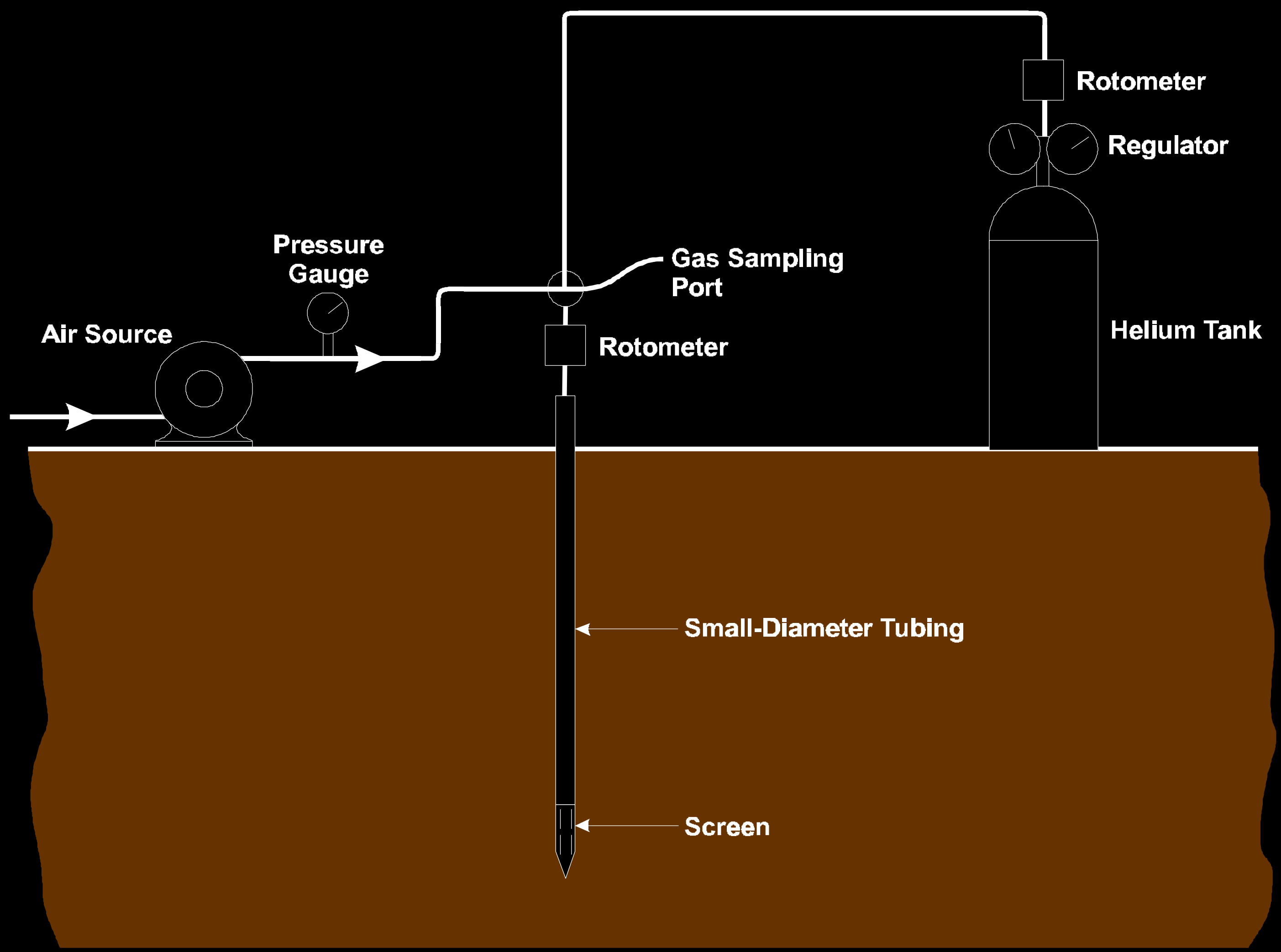
In Situ Respiration Test Procedure

- Oxygenate soils
  - Initial tests via monitoring points (see next figure)
  - Interim tests via air injection or withdrawal system
- Conduct test in the contaminated and in an uncontaminated area
- Inject helium with air during initial test
- Measure oxygen uptake

Typical Monitoring Point Construction



In Situ Respiration Test Apparatus



In Situ Respiration Testing Considerations

- Purpose of uncontaminated area
  - Measure background oxygen utilization
    - microbial metabolism of natural organic matter
  - Measure non-biological oxygen utilization
- Purpose of helium injection
  - Check for diffusion of injected gases
  - Check for leakage of monitoring points
  - Rule of thumb: if He drops below 50% of initial concentration by end of test, test is invalid

Interpretation of In Situ Respiration Results

- Evaluate test validity
- Calculate oxygen utilization rate (k_O)
- Convert to biodegradation rate (k_B) to determine amount of fuel degraded

Calculation of Biodegradation Rate

$$C_6H_{14} + 9.5\ O_2 \longrightarrow 6\ CO_2 + 7\ H_2O$$

$$K_B = \frac{{}^{-}(K_o)(\text{porosity})(O_2\ \text{density})(C)(0.01)}{(\text{bulk density})}$$

where C = mass ratio of contaminant to oxygen

Biodegradation Rates

- Typically between 2 to 20 mg/kg-day
- Rates are a function of contaminant concentration
  - Rates tend to be high when contamination is high
  - Rates decrease as site is cleaned up and contamination levels decrease

Interpretation of In Situ Respiration Test Results at AOC A, Keesler AFB

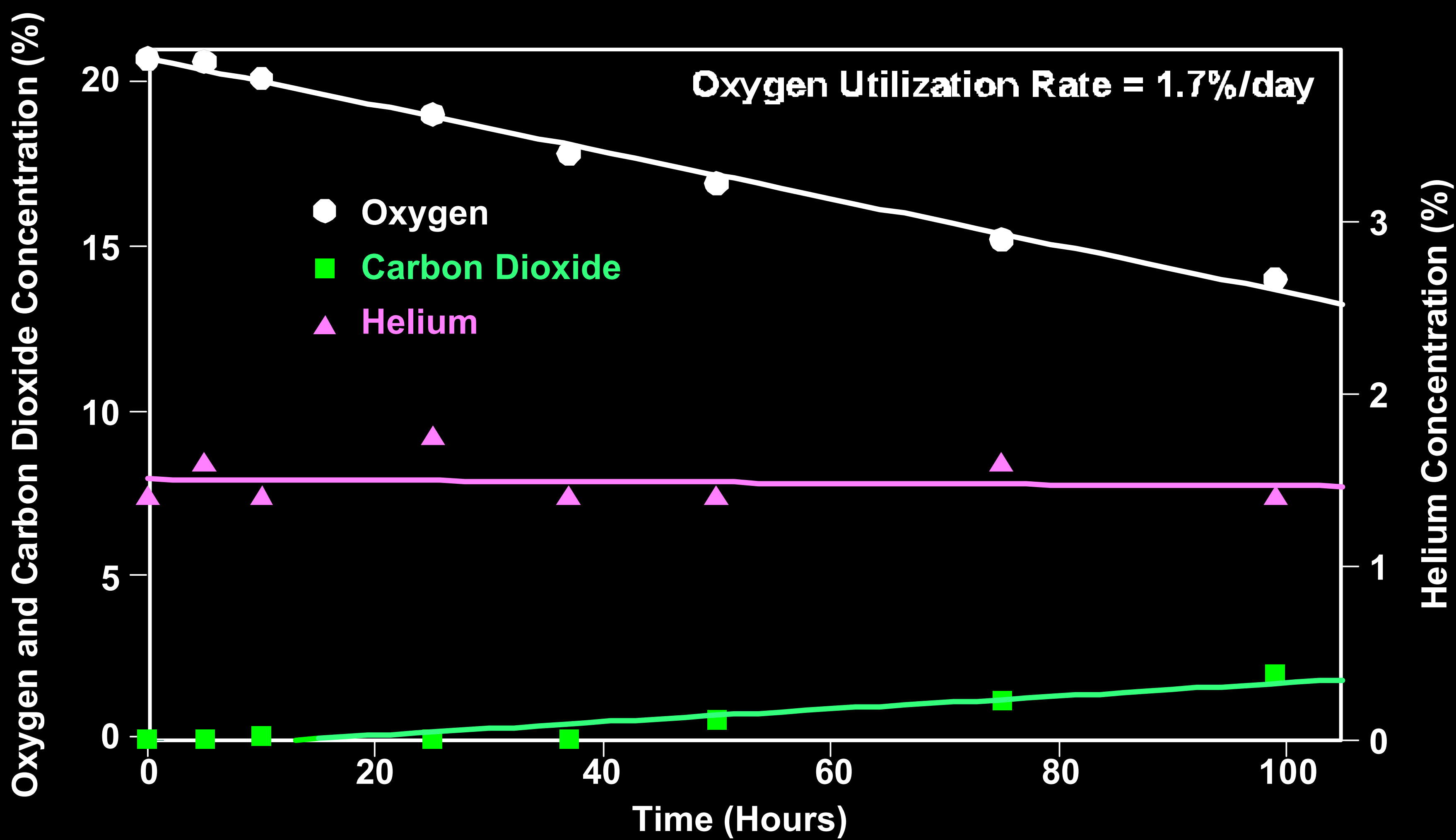
Initial Soil-Gas Readings

Monitoring Point	Depth (ft)	O_2 (%)	CO_2 (%)	TPH (ppm)
K1- MPA	5.0	0.4	15	>100,000
	7.0	0.6	15	>100,000
K1-MPB	4.0	0.5	15	>100,000
K1-MPC	7.0	0.5	15	29,000

Typical In Situ Respiration Test Data

Time (hr)	O_2 (%)	CO_2 (%)	He (%)
0	20.6	0	1.6
5	20.2	0	1.8
10	19.4	0	1.8
25	16.9	0	1.6
37	14.8	0	1.4
50	12.9	1.0	1.4
75	9.9	2.6	1.2
99	8.0	3.0	1.2

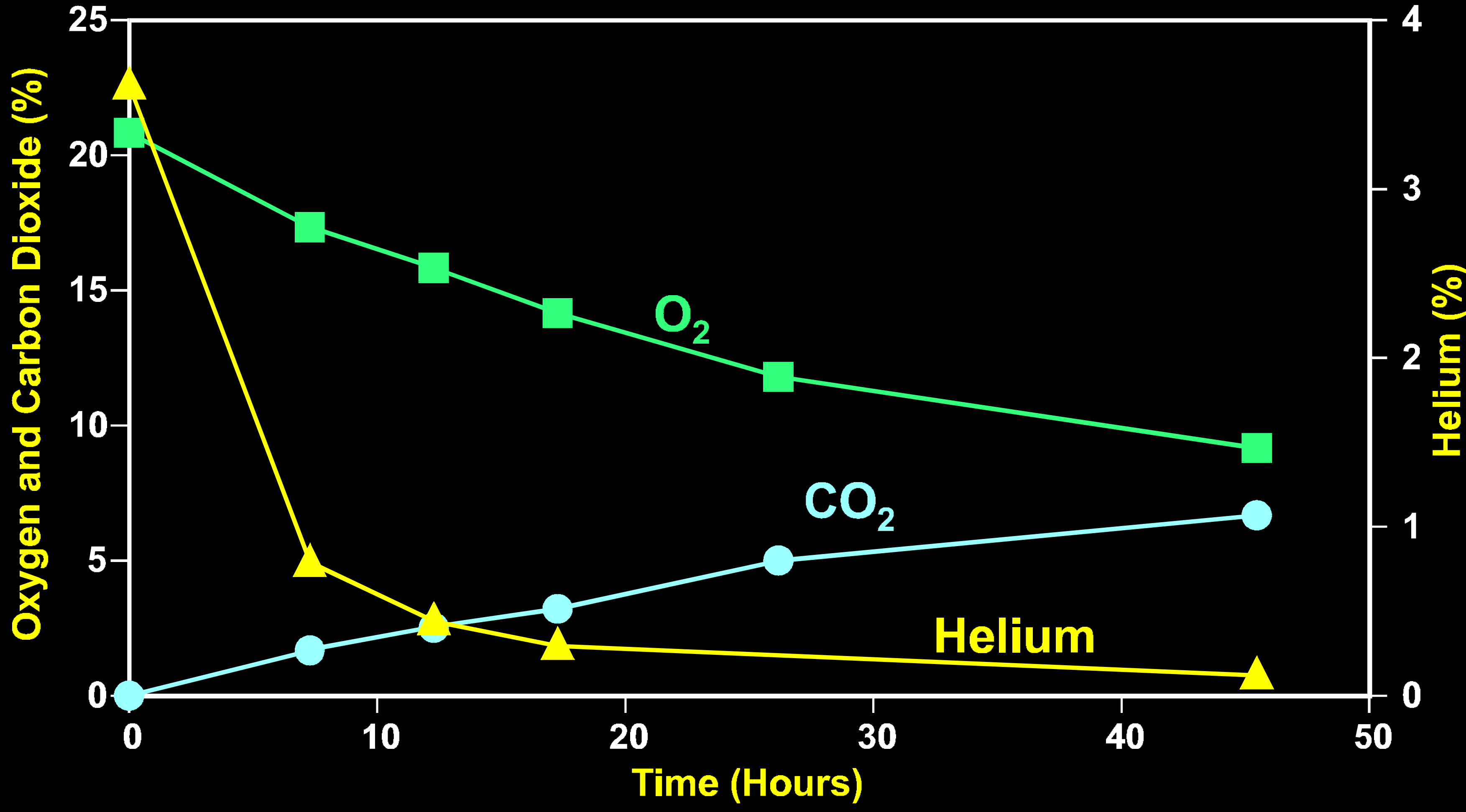
Typical In Situ Respiration Test Results
Keesler AFB, MS



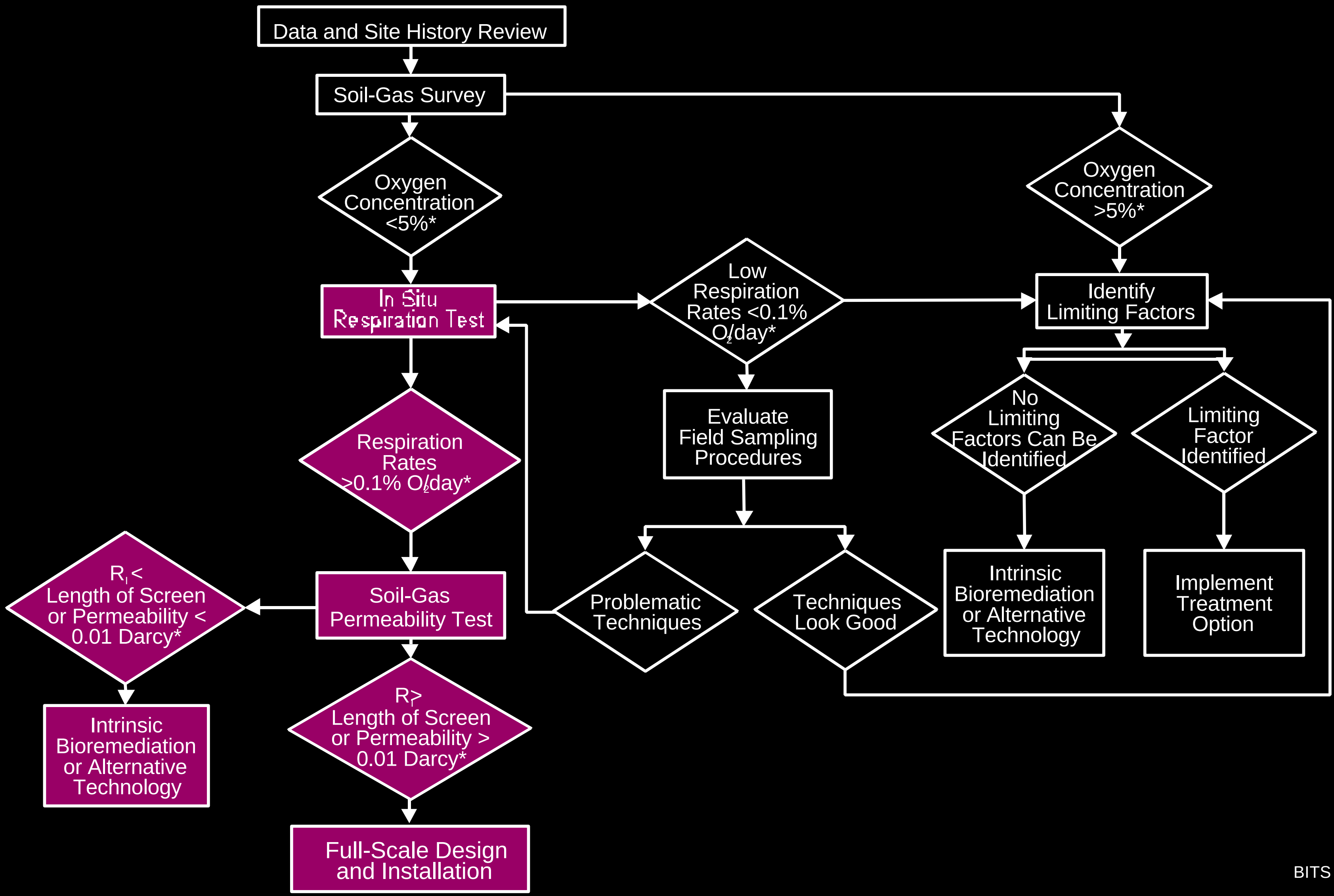
Oxygen Utilization Rates at AOC A, Keesler AFB

	O_2 rate (% hr)	Biodegradation rate (mg/kg-day)
K1-MPA-5.0	0.071	1.2
K1-MPA-7.0	0.045	0.73
K1-MPB-5.0	0.13	2.1
K1-MPC-7.0	0.099	1.6

In Situ Respiration Test Results with Unacceptable Data Based on Helium Concentration



Flow Chart for Determining the Potential Applicability of Bioventing at a Contaminated Site: Soil-Gas Permeability Test



Soil-Gas Permeability

- Soil s capacity for fluid/air flow
- Varies according to
  - soil type
  - porosity
  - moisture content

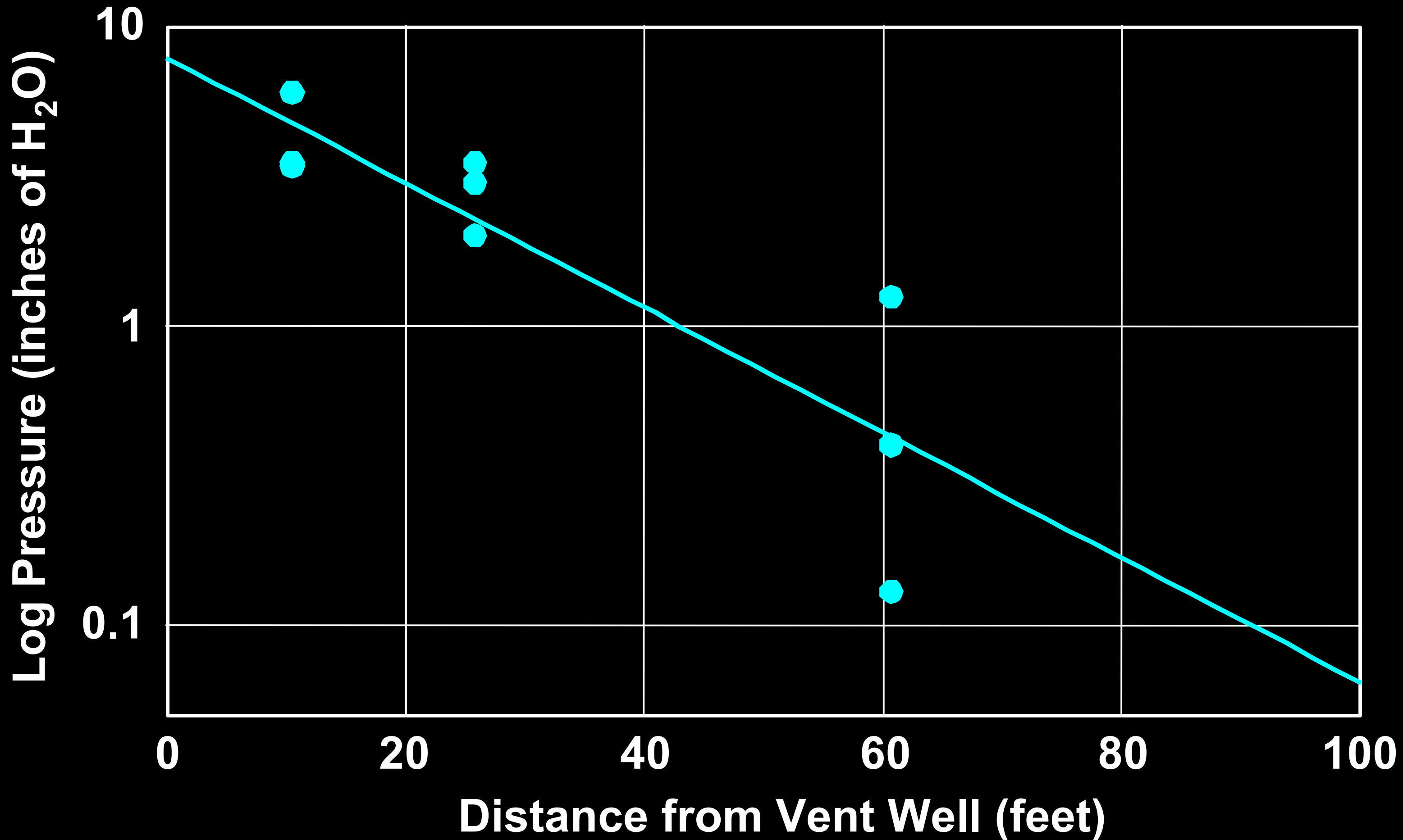
Permeability Test

- Inject air at steady flow and pressure into a vent well
- Monitor pressure change at monitoring points
- Determine radius of influence of system

Radius of Influence

- Most important parameter from permeability test for bioventing design
- Plot log pressure change versus distance from vent well
- Empirically, radius of influence is that distance where 0.1 inches of water pressure can be measured
- Radius of influence can vary from 10 to 200 ft, depending on permeability and depth to groundwater

Typical Calculation of Radius of Influence Galena AFS, AK



Soil-Gas Permeability Values

Soil Type	k in Darcy
Coarse sand	100 to 1,000
Medium sand	1 to 100
Fine sand	0.1 to 1.0
Silts/clay	<0.1

1 darcy = 10^{-8} cm^2

Johnson, P.C., C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart. (1990).
"A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems."
Groundwater Monitoring Rev., 10(2): 159-178.

Soil Borings

- Located based on data review and/or soil-gas survey
- Borings can be used for soil sample collection and installation of wells and monitoring points

Soil Sampling

- Contaminant of concern
  - At a fuel spill site: TPH and BTEX
  - Chlorinated compounds: parent compound, possible intermediates
- Moisture content
- Total Kjeldahl nitrogen
  - Measure of all nitrogen sources in soil
- Other parameters such as alkalinity, pH, phosphorus, microorganism count, are not necessary for system design

System Design

- Determination of air flow system
  - Injection versus extraction
  - Protection of structures
- Determination of air flowrates
- Well spacing
- Blower sizing
- Vent well construction
- Monitoring point construction

Bioventing Design

- Should I add microorganisms?
  - ***NO!!***
- Should I enumerate or count microorganisms?
  - Probably not...
    - many enumerations have been done and generated little useful data
    - identity of bugs may be of academic curiosity, but of little engineering value

Bioventing Design

- Are nutrients required?
  - ***Usually not!***
  - Compare oxygen utilization rates to literature. Only consider nutrient addition if rates are consistently low, moisture is adequate, and contamination is high
  - Be wary of laboratory-scale tests (do not correlate well with field results)

Why Don t Nutrients Help?

- Low microbial activity
- Nutrient recycling
- Difficulty in nutrient addition in situ
  - Hard to apply uniformly
  - Expensive

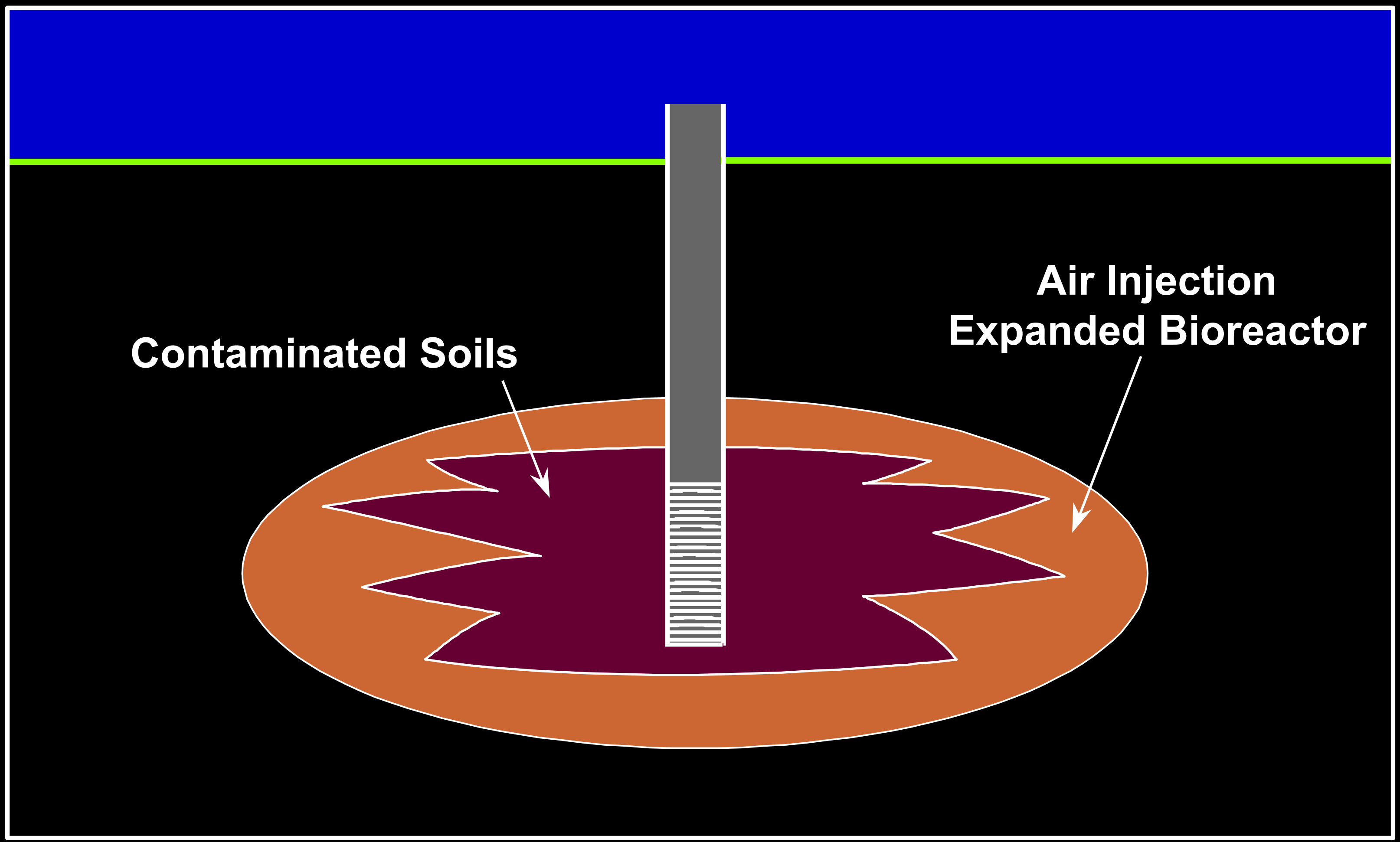
Air Injection Usually the Method of Choice

- Lowest air flowrates
- Lowest emissions
- Lowest capital costs
- Lowest maintenance

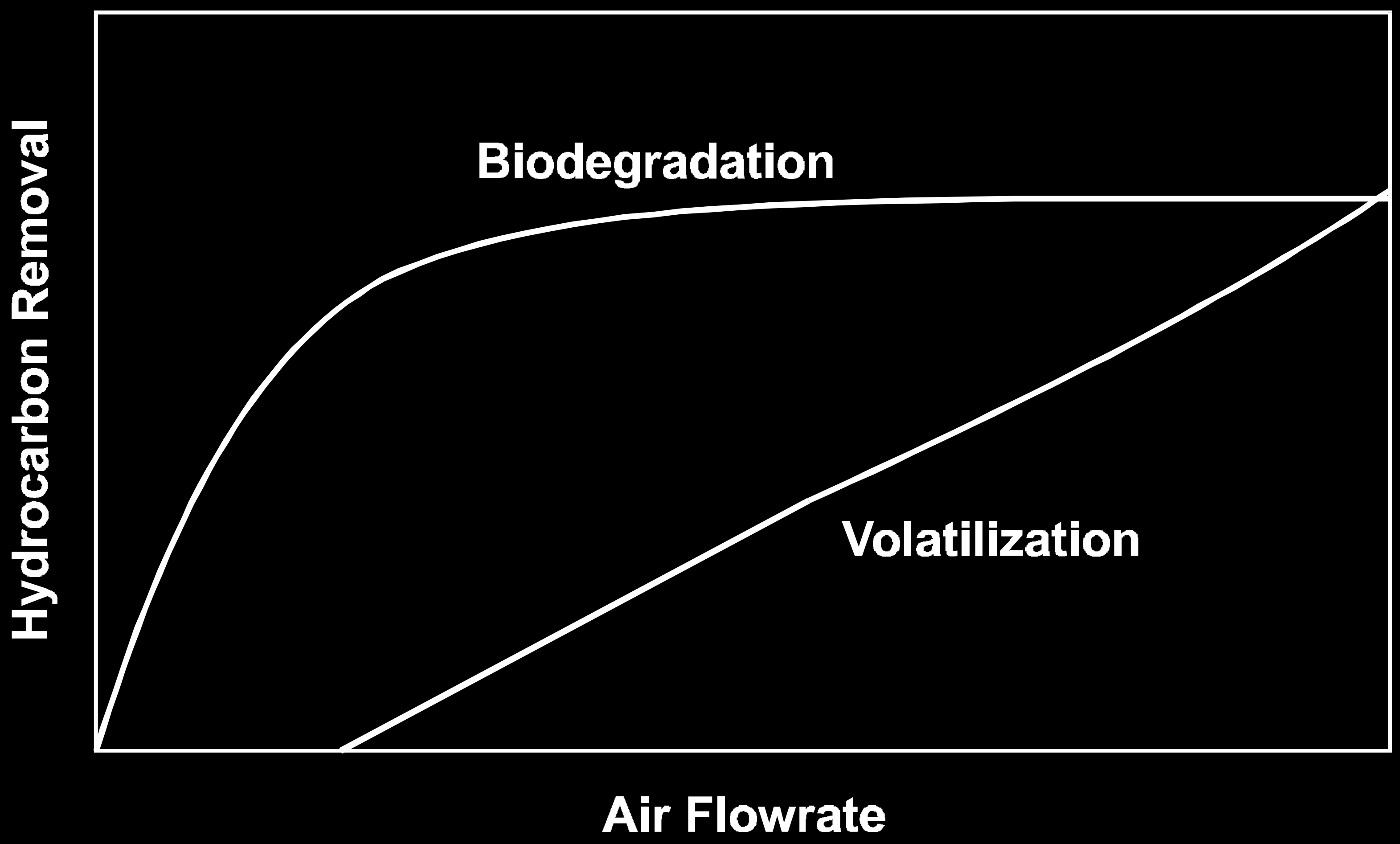
Air Delivery Systems

- Air injection
  - Actively inject air via blower system
- Passive venting
  - Capitalize on natural barometric pressure fluctuations or tidal influences to aerate contaminated areas
- Air extraction

Expanded Bioreactor Created During Air Injection



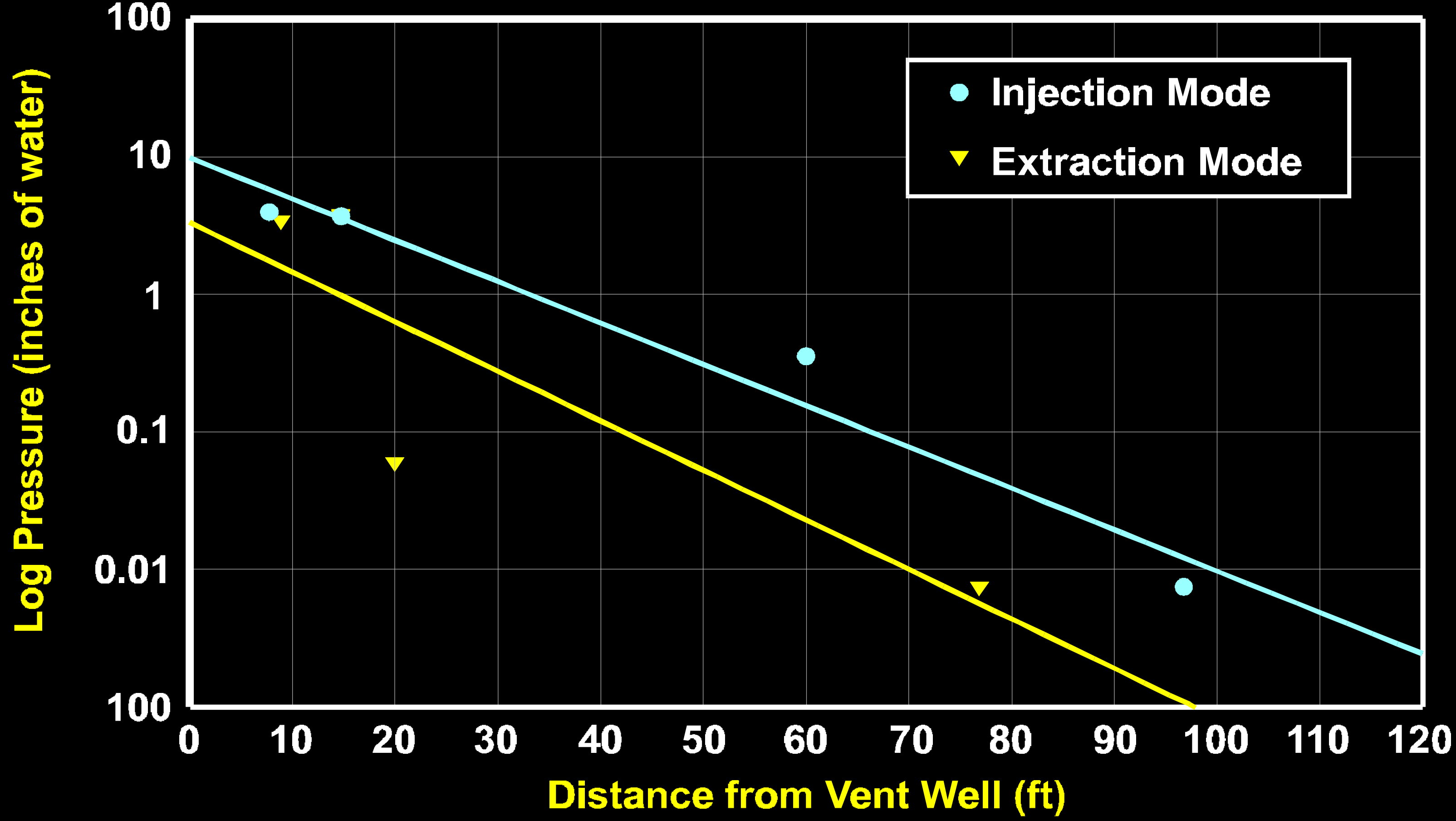
Hydrocarbon Biodegradation and Volatilization Rates as a Function of Flowrate



Air injection has the potential to expose more contaminated soil to treatment

air extraction may prevent some areas from being exposed to treatment due to water table fluctuation

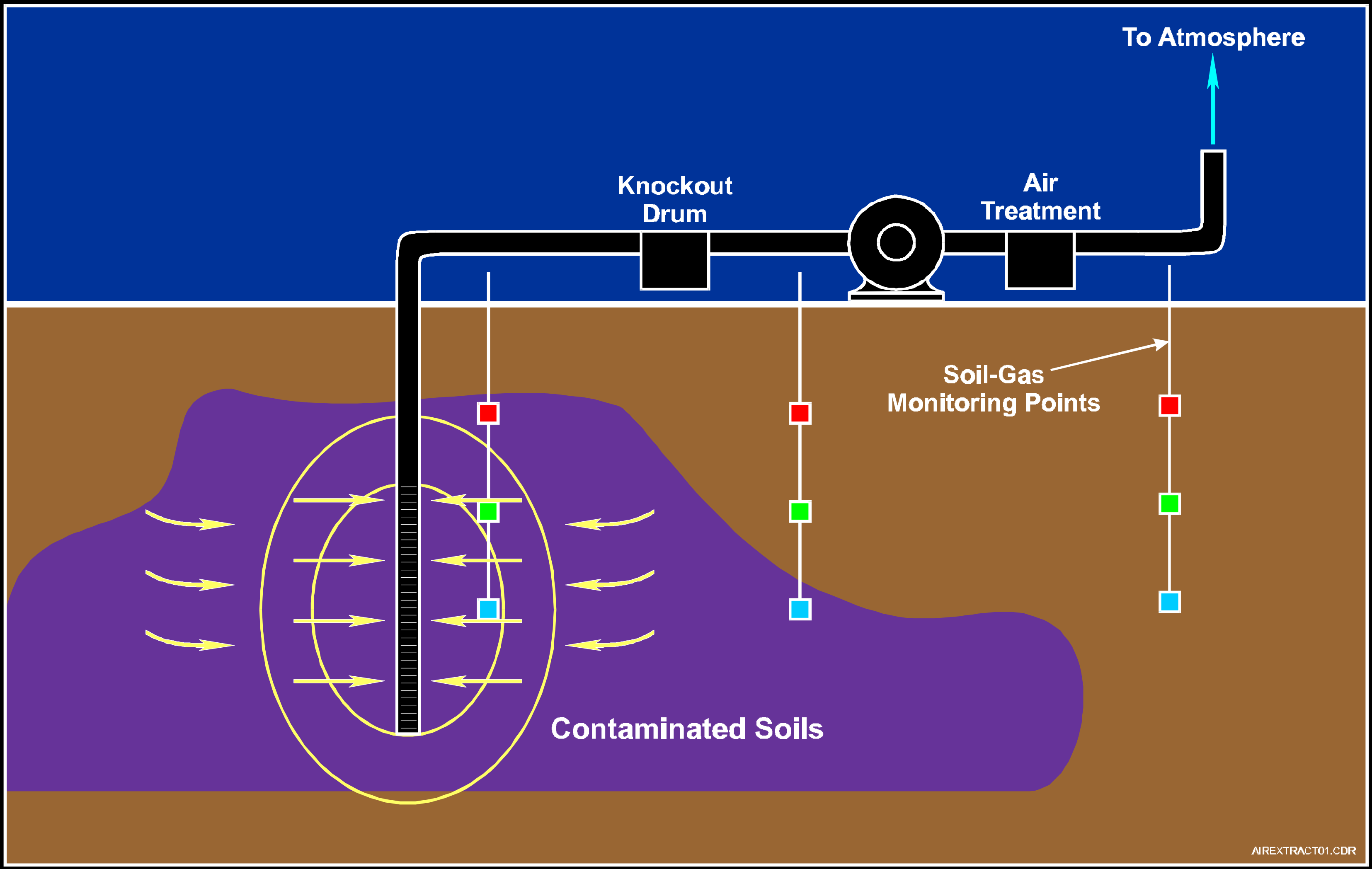
Radius of Influence During Air Injection and Air Extraction



Air Extraction May be Necessary at Some Sites

- Problems with subsurface structures
- Excessive surface emissions

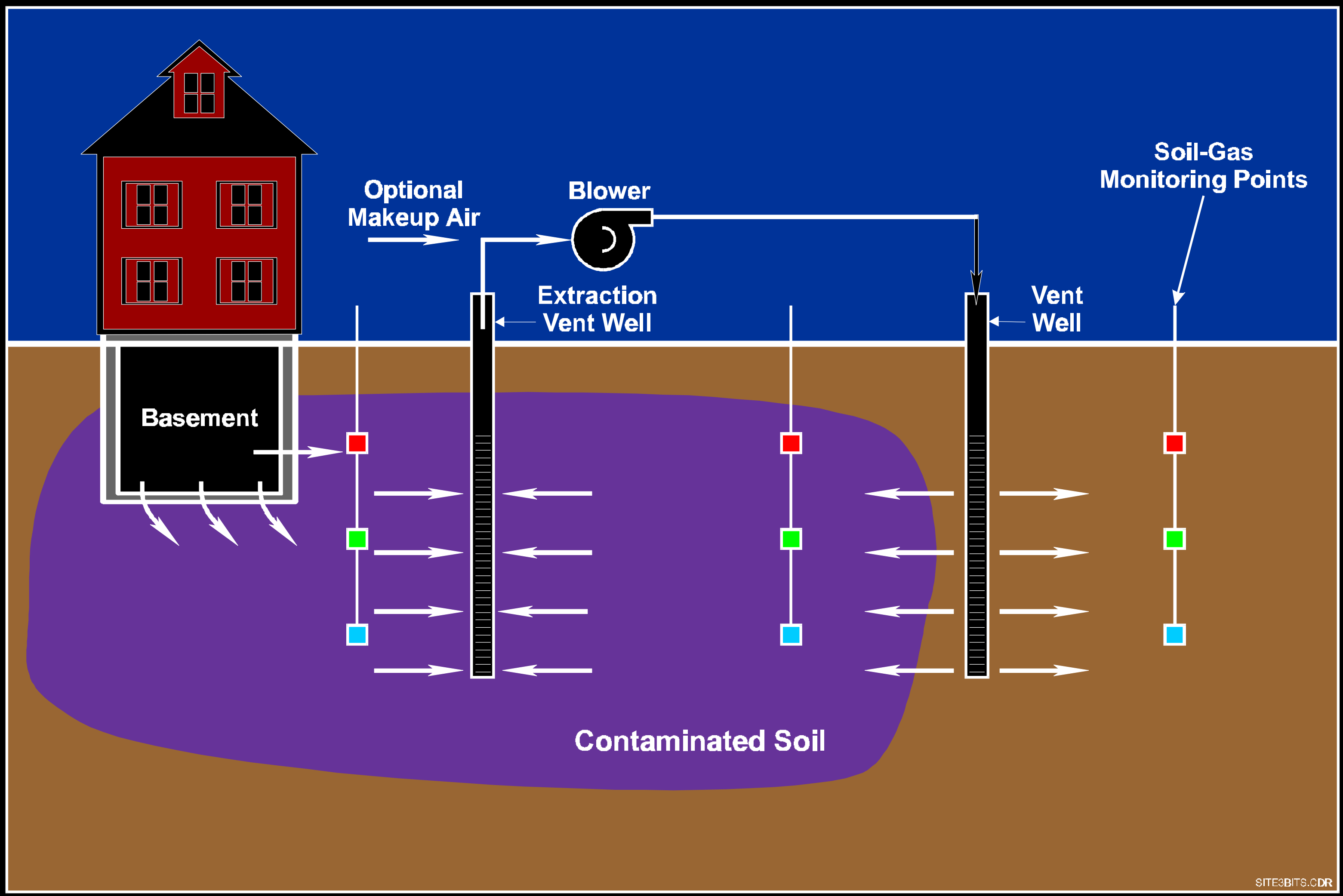
Basic Air Extraction System



Alternatives to Direct Extraction with Emission

- Isolation of subsurface structure
- Reinjection

Air Injection System with Reinjection of Extracted Soil Gas



Determination of Air Flowrates

- Based on oxygen utilization rate
- Use oxygen utilization rate measured at peak activity (typically late summer)
- Minimum level of 5% O_2 should be maintained in treatment area
- Typical values range from 10 to 50 cfm
- Detailed equation in Bioventing Manual, Volume II

Calculation of Design Air Injection Rate

$$k_o = \frac{-k_b \cdot r_s}{q_a \cdot r_{O_2} \cdot C}$$

$$Q_{air} = \frac{-p \cdot R_i^{\,2} \cdot d \cdot k_b \cdot r_s}{r_{O_2} \cdot C \cdot [O_2]}$$

Where:

Q_{air}	design air injection rate, scfm
k_b	in situ biodegradation rate (determined by in situ respiration test), mg/kg-day
k_o	oxygen utilization rate, 1/day[a]
q_a	gas-filled pore space, cm^3 gas/cm^3 soil
ρ_{O_2}	density of oxygen gas, mg/L
C	mass ratio of hydrocarbon to oxygen required for mineralization, g HC/g O_2
ρ_s	bulk density of soil, g/cm^3
R_i	Radius of influence, m
d	depth to bottom of venting screen, m
$[O_2]$	oxygen content in air, dimensionless constant

a express oxygen content consumed as a dimensionless fraction per day (for example 8%/day should be expressed as 0.08/day)

Blower Selection

- Centrifugal machines
  - Single stage radial blower
  - Regenerative blower
- Positive displacement machines
  - Rotating machines
  - Reciprocating machines

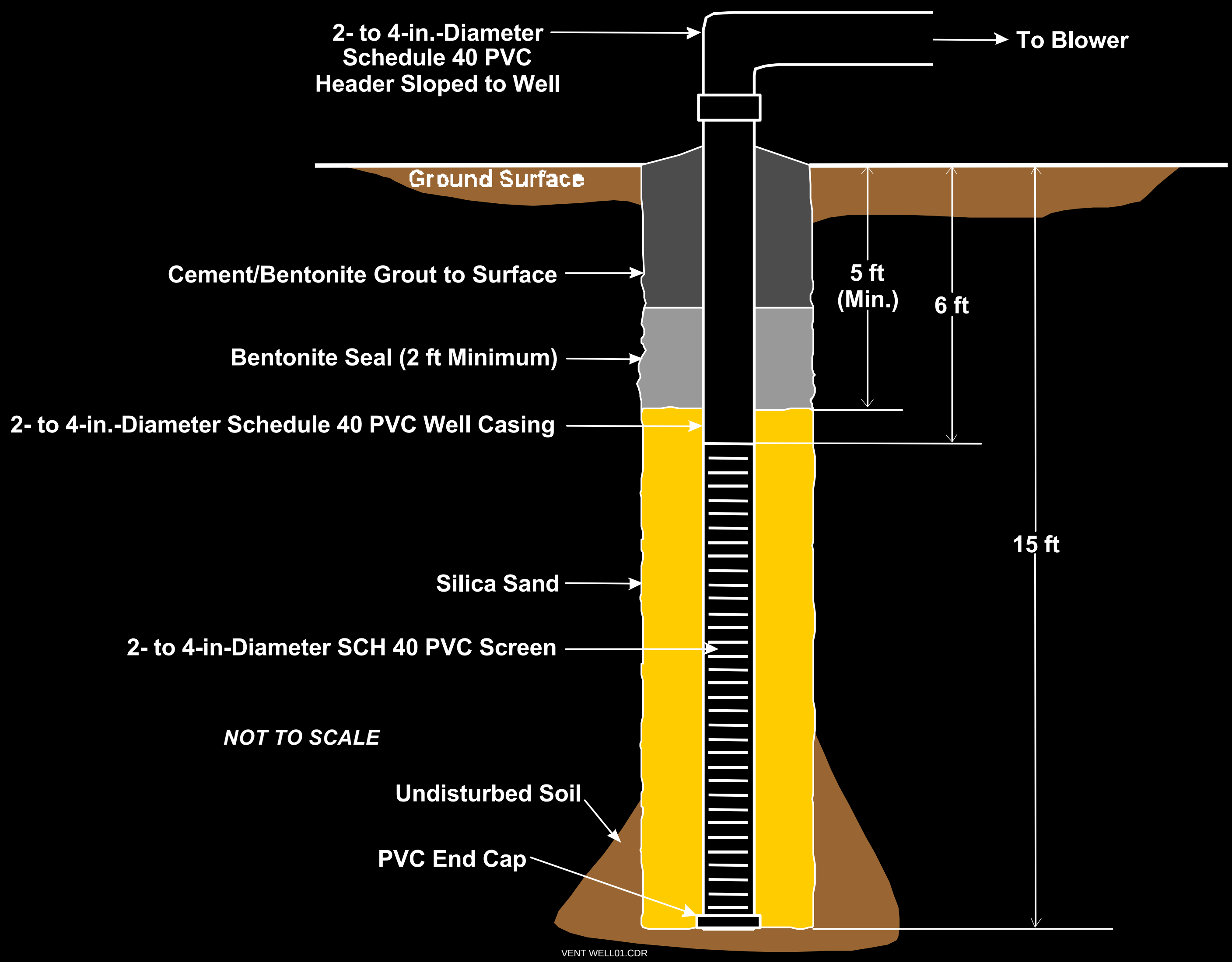
Blower Selection

- Selection is based on air flow requirements and pressures determined in the field during the soil-gas permeability test
- High air flow, low operating pressure
  - Centrifugal pumps
- Low air flow, high operating pressure
  - Rotating positive displacement pumps

Vent Well Construction

- Spacing typically 1.5 to 2 times the radius of influence
- Typically, 2- to 4-inch-diameter PVC
- Screen should extend through as much of the contamination as possible, with bottom corresponding to lowest historical water table level

Typical Vent Well Construction



Monitoring Point Construction

- Locate in contaminated soil
- Position considering soil-gas permeability test: minimum 3 locations from vent well
- Generally, 3 depths
  - Deepest, at bottom of contamination
  - Shallowest, 3 to 5 ft below ground surface

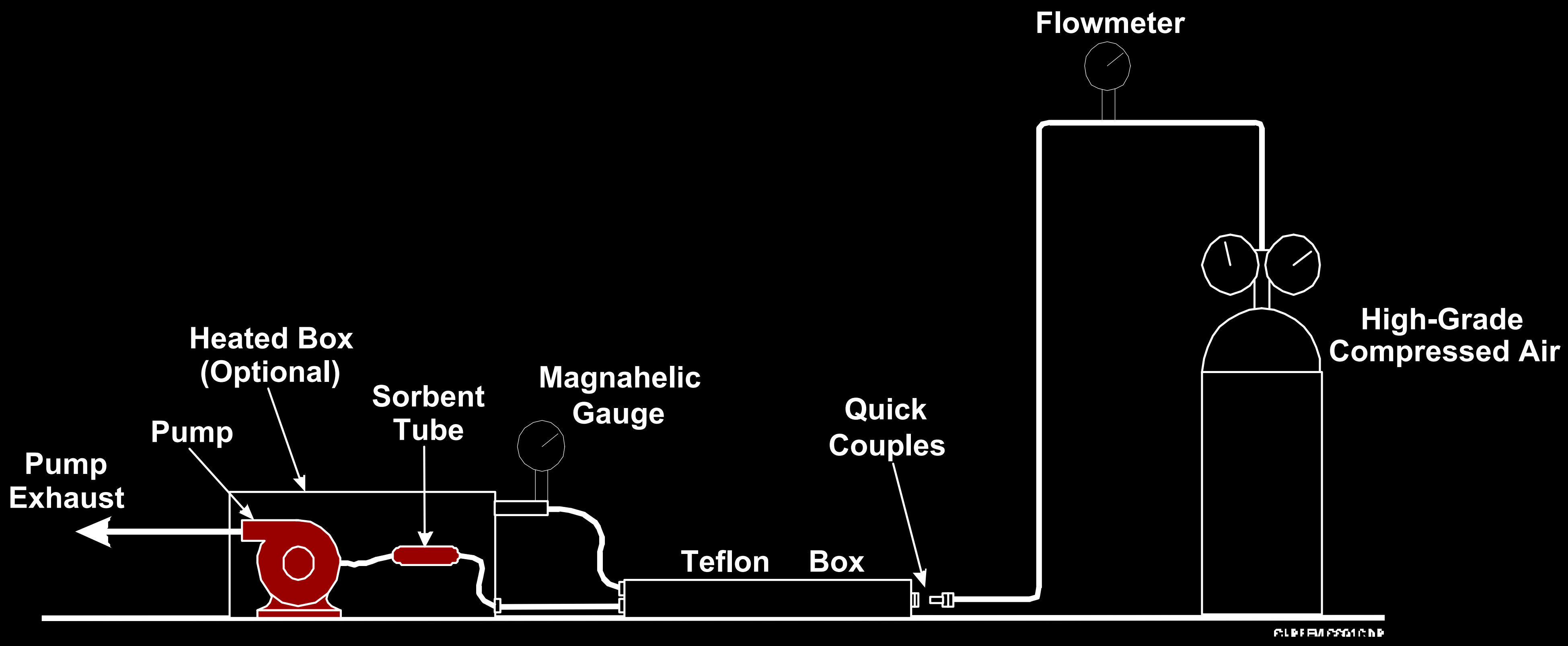
Monitoring Point Spacing

Soil Type	Depth to Top of Vent Well Screen (ft)	Spacing Interval
Coarse sand	5	5-10-20
	10	10-30-50
	>15	20-30-70
Medium sand	5	10-20-30
	10	15-25-45
	>15	20-40-70
Fine sand	5	10-20-40
	10	15-30-50
	>15	20-40-60
Silts	5	10-20-40
	10	15-30-50
	>15	20-40-60
Clay	5	10-20-30
	10	10-20-40
	>15	10-25-50

Performance Monitoring

- Soil-gas
- In situ respiration test
- Optional measurements: generally regulatory-driven
  - Quantification of biodegradation versus volatilization
  - Surface emissions

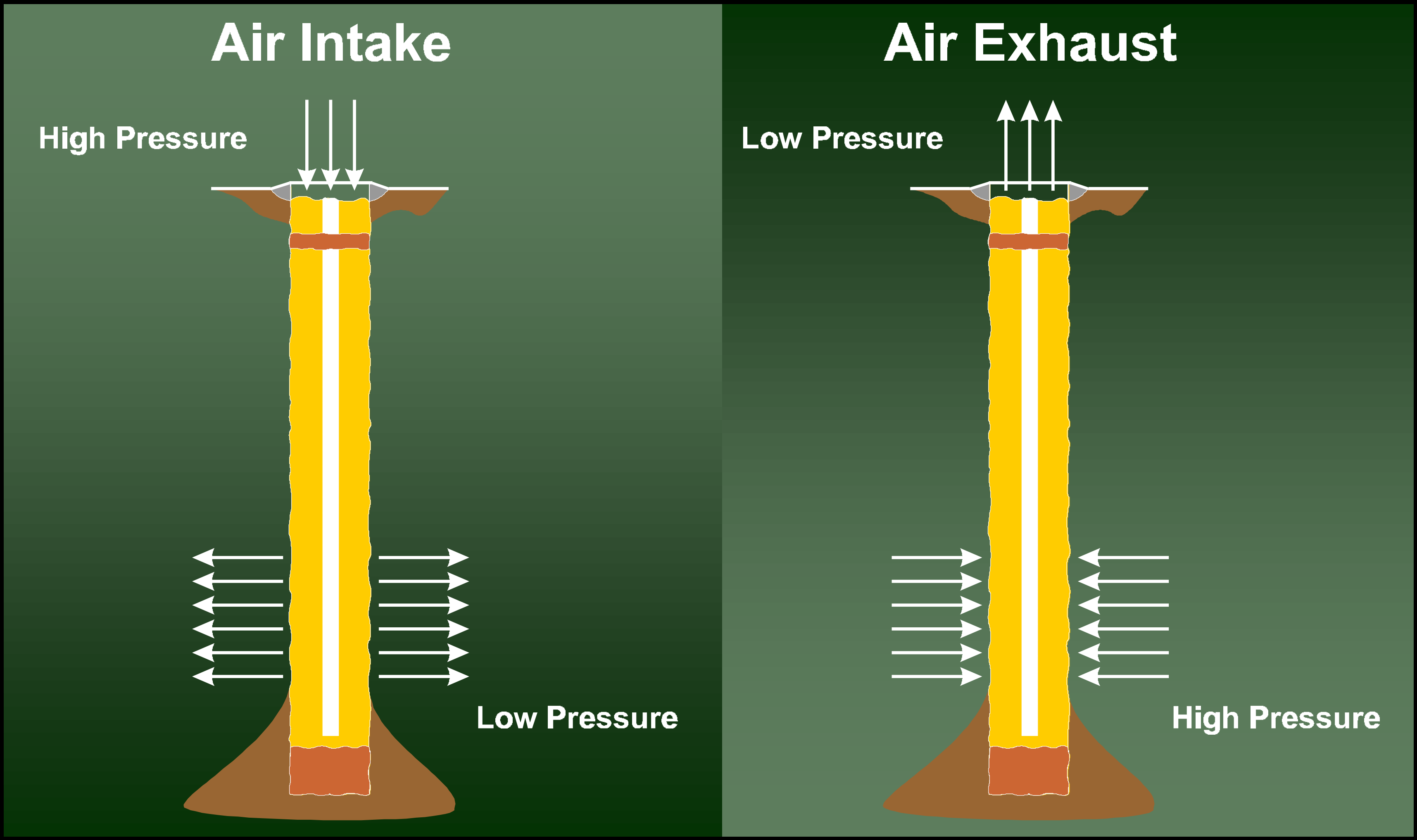
Surface Emissions Monitoring Device



Bioventing Monitoring

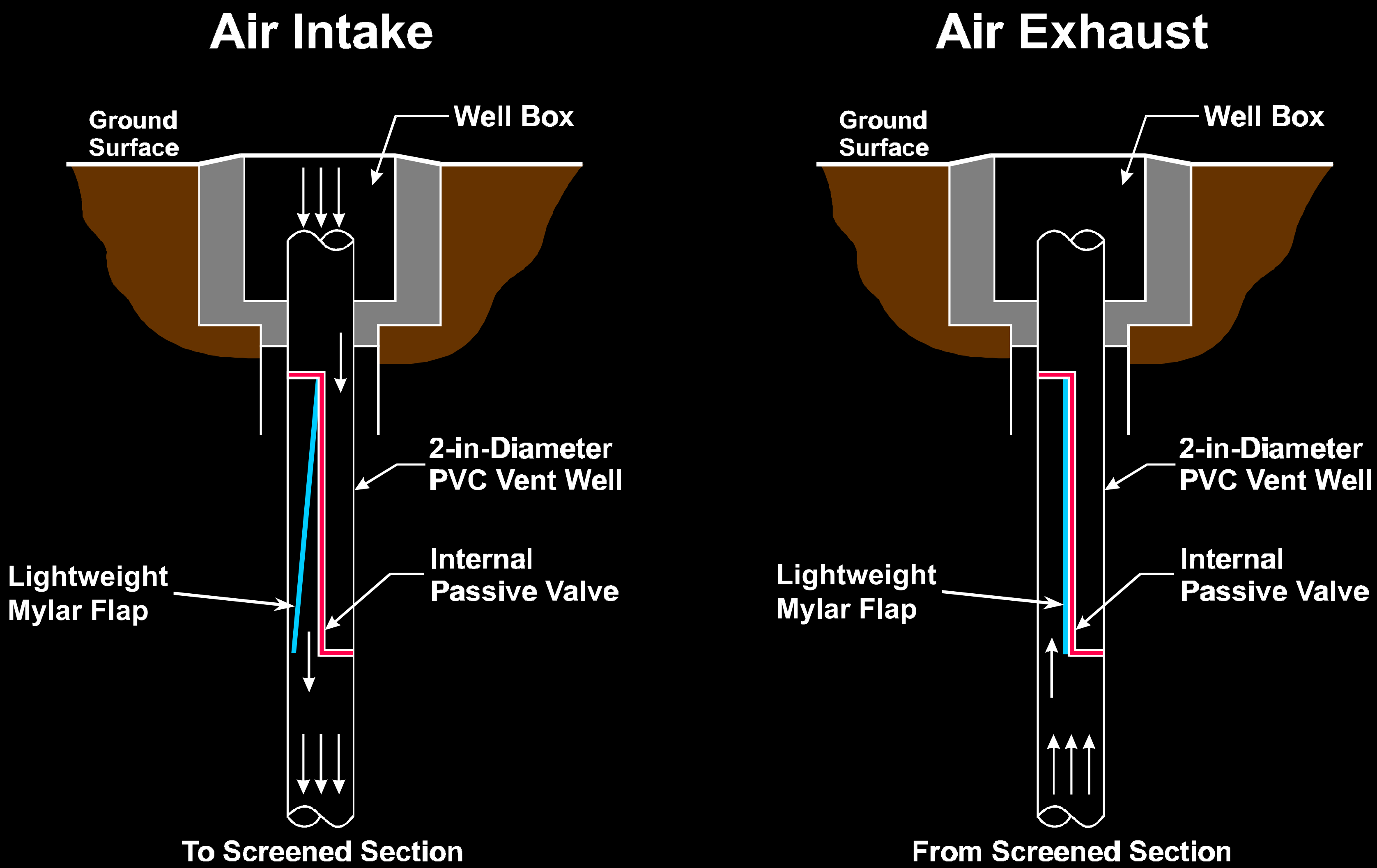
- In situ respiration test
  - Year 1 semi-annually
  - Year 2 to closure annually
- When oxygen utilization approaches 0, initiate final sampling
- *No periodic soil sampling needed!!*

Airflow in Response to Barometric Pressure

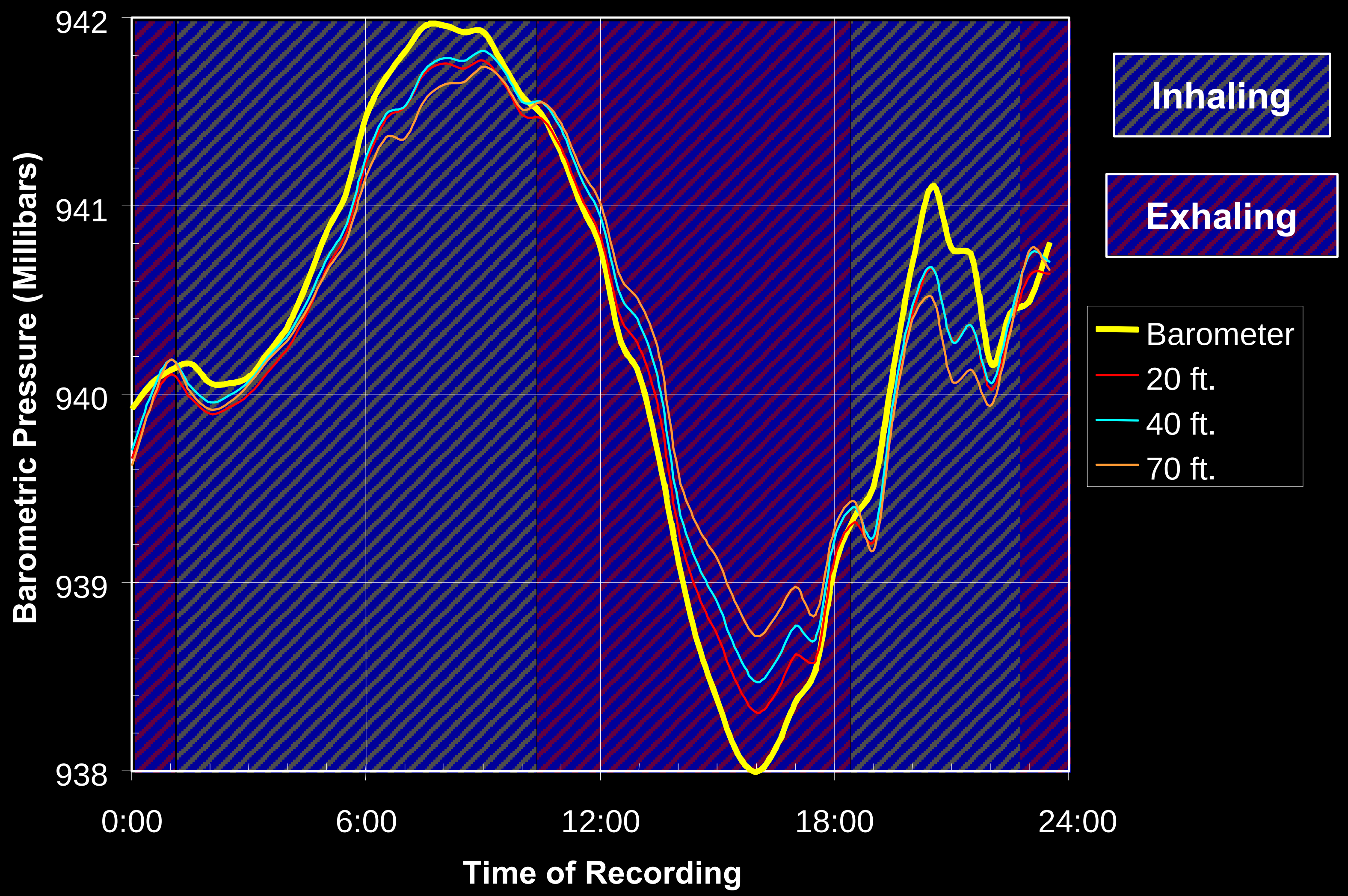


NOT TO SCALE

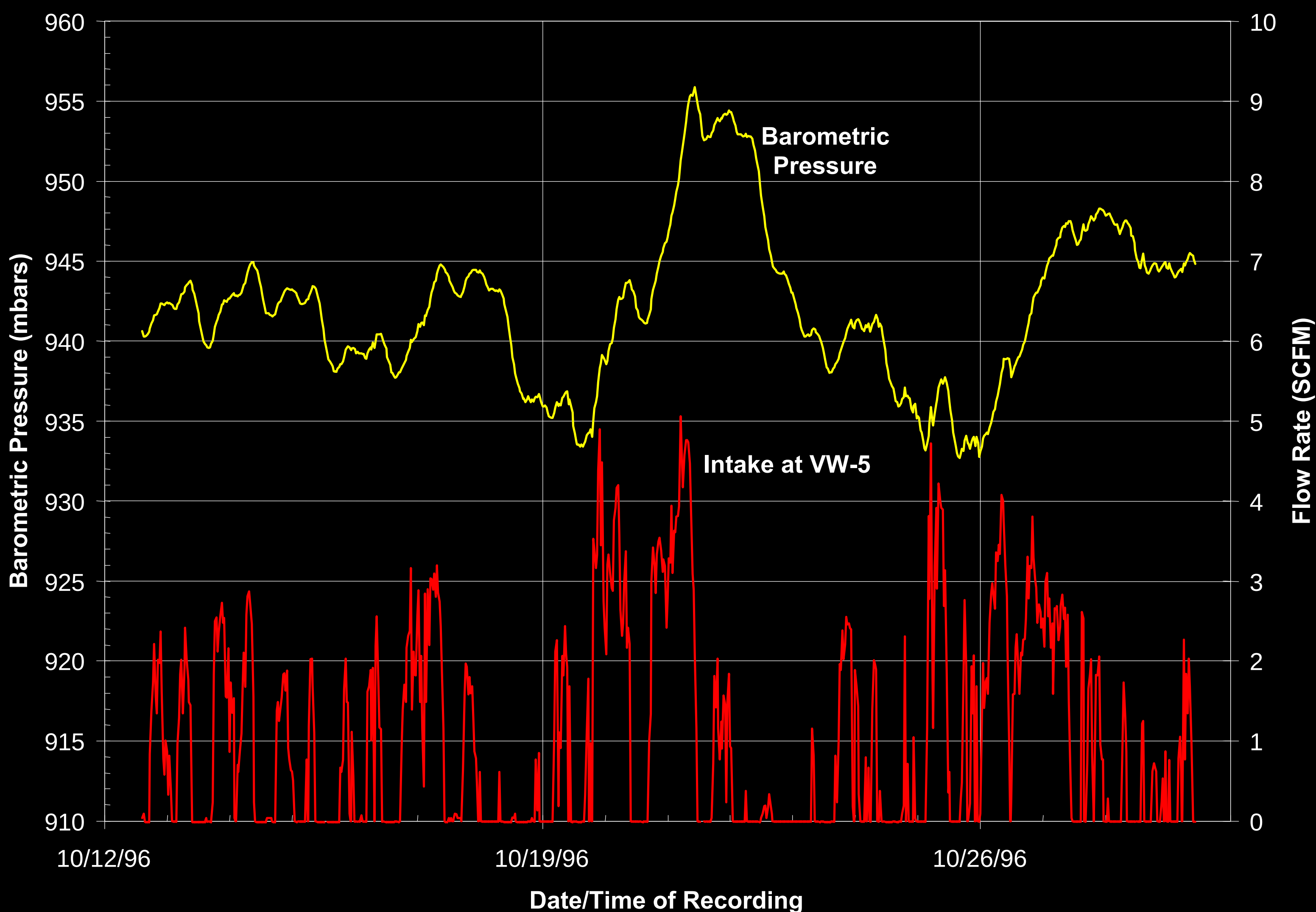
Schematic of the Passive Valve



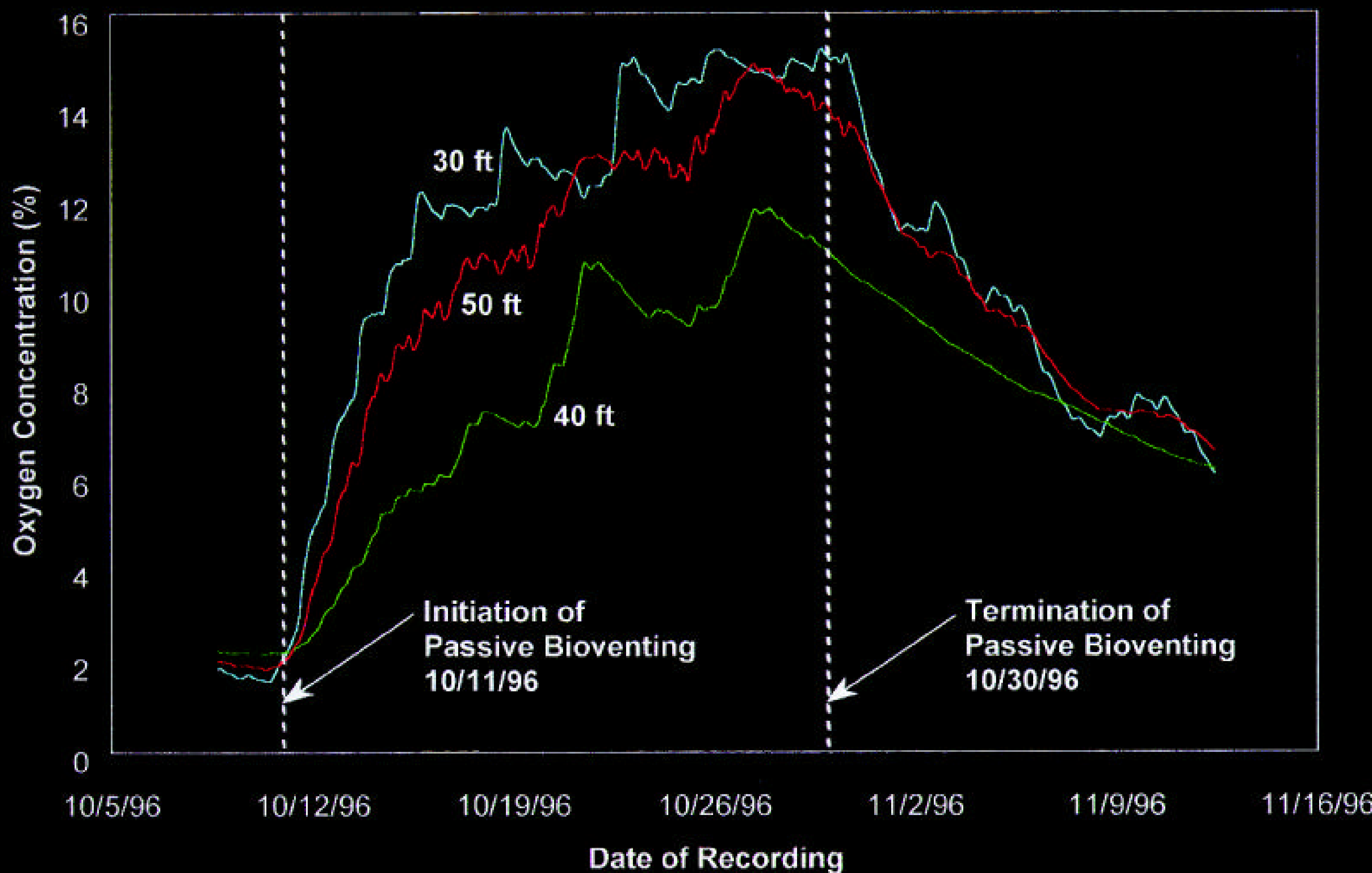
Diurnal Barometric and Soil Gas Pressures Measured During Phase 1



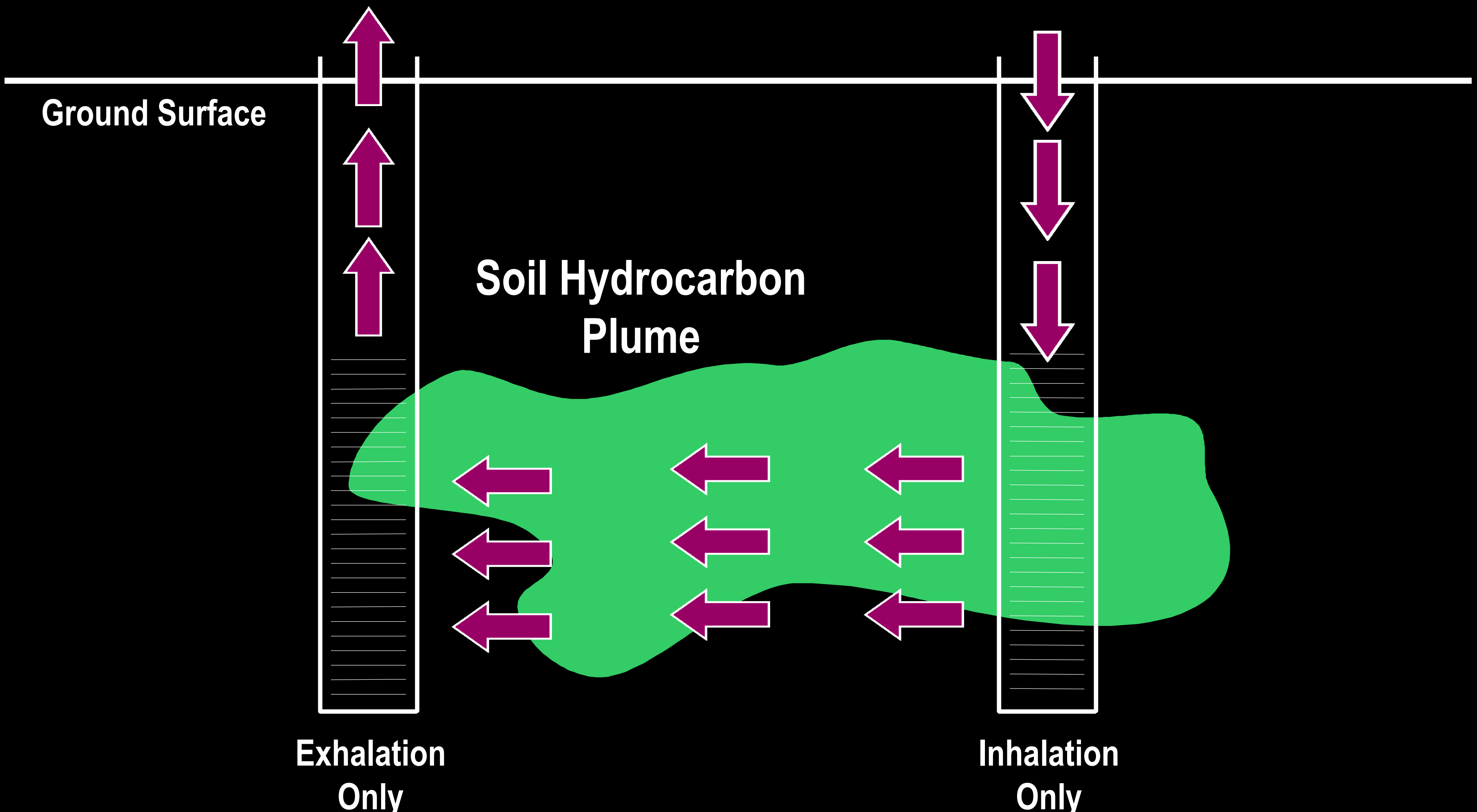
Results of Phase 3 Study at Site 17 MCAGCC



Oxygen Concentrations During and Following Passive Aeration in Phase 3



Push/Pull Concept



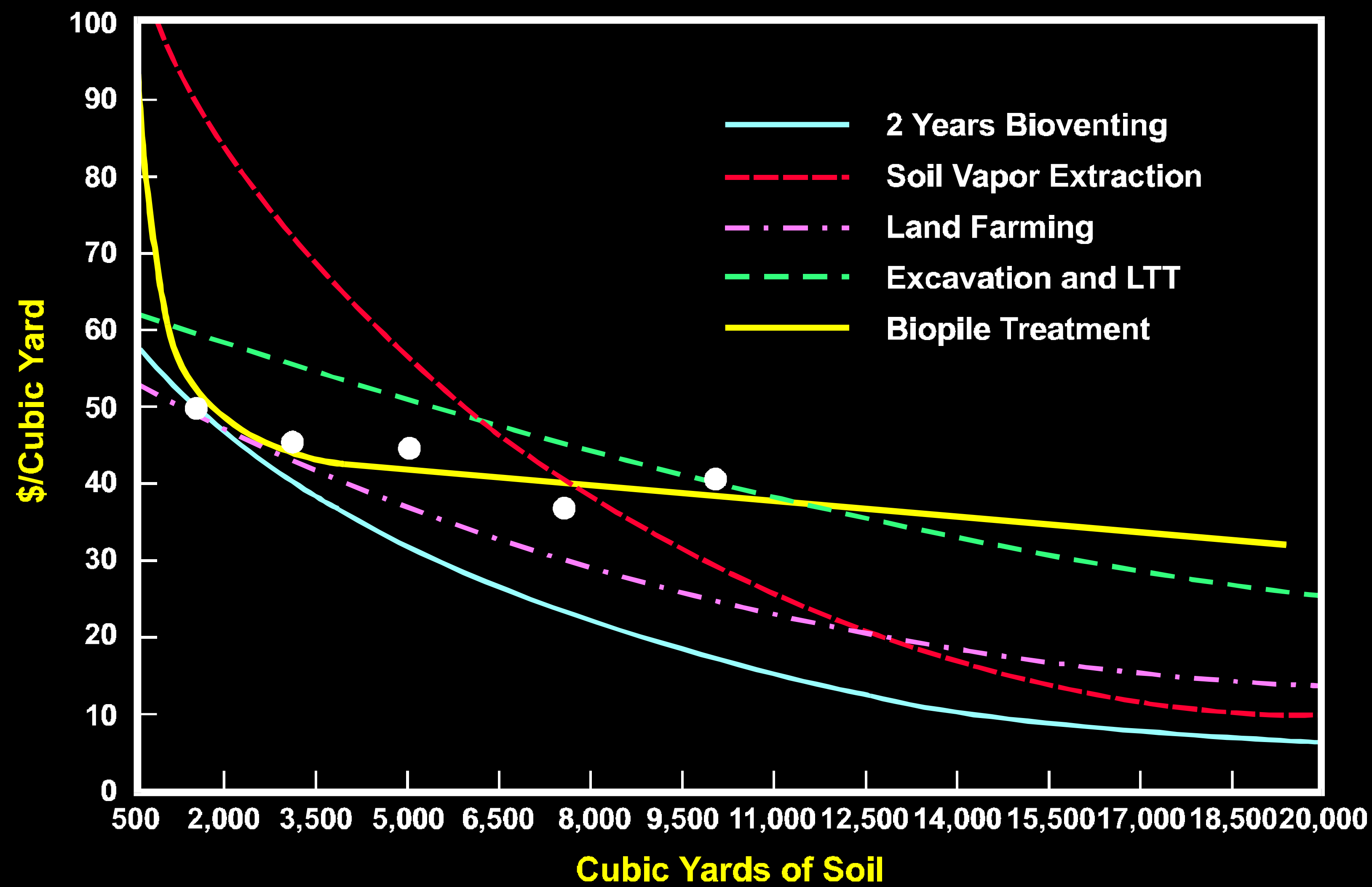
Cleanup Times and Costs are Site Specific

- Soil characteristics
- Contaminant location and distribution
- Soil moisture content
- Contaminant concentration
- Desired cleanup time
- Air emissions

Full-Scale Bioventing Costs

Task	Total Cost ($)
Site visit/planning	5,000
Work plan preparation	6,000
Pilot testing	27,000
Regulatory approval	3,000
Full-scale construction	
Design	7,500
Drilling/sampling	15,000
Installation/startup	4,000
2-yr monitoring	6,500
2-yr power	2,800
Soil sampling at 2 years	13,500
TOTAL	**90,300**

Comparison of Costs for Soil Treatment



Closure

- 2-10 years for TPH
- 1 year for BTEX
- Sample soils to verify cleanup

Bioventing Limitations

- Process is slow, requiring months to years
- Process will not work if:
  - Contaminants are not biodegradable
  - Soil-gas flow cannot be induced

Documents Available

- Bioventing Manual
- Bioventing Cost Estimator
- Bioventing Statement of Work Guidance Document

Bioventing Manual

- Principles of bioventing
  - Physical and chemical processes
  - Microbiological processes
- Site characterization
- Design
- Process monitoring
- Site closure

Bioventing Cost Estimator

- Uses prices for actual bioventing projects
- Calculates quantities of materials required using engineering design equations
- Estimates cost of pilot-scale investigation
- Estimates full-scale installation, operation, and maintenance costs

Bioventing Statement of Work Guidance Document

- Provides overview of bioventing
- Details objectives of Statement of Work
- Covers design, installation, operation, maintenance, and closeout
- Includes:
  - Definition of data required for design
  - Description of required features
  - Description of optional characteristics